No. 2

A/AC 105/468

SEMINARS

of the United Nations Programme on Space Applications

Selected Papers on Remote Sensing and Satellite Communications
1991

United Nations

READEX
FICHE

Outer Space Affairs Division

A/AC.105/468

SEMINARS
of the
United Nations Programme on Space Applications

Selected Papers on Remote Sensing and Satellite Communications
1991

United Nations
1991

Foreword

Since 1972, the United Nations Outer Space Affairs Division, as part of its Programme on Space Applications, has organized and co-sponsored meetings, seminars, training courses and workshops on the applications of space technology in order to assist developing countries in establishing indigenous technological infrastructure and in developing and implementing local programmes. The United Nations carries out these activities in co-operation with other international and regional organizations and national institutions in accordance with the mandate of the Programme, relevant United Nations General Assembly resolutions, and the recommendations of the Second United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE 82). UNISPACE 82 had re-affirmed the importance of establishing and strengthening national and regional mechanisms to promote co-operation in the use of space technology for the benefit of developing countries. The Programme on Space Applications conducts a number of activities that are devoted to various fields of space technology. In 1990 it organized activities dedicated particularly to (a) improving information systems in agricultural, geological, oceanographic and coastal resources through remote sensing techniques, (b) satellite communication for development, and (c) development of indigenous capability at the local level particularly through educational systems. This publication comprises selected papers presented as part of the 1990 activities of the Programme.

The scope of the publication extends from a general overview of the use of remote sensing technology for development to specific areas of application, including the assessment of natural vegetation and agricultural systems, the determination and forecast of precipitation, the monitoring of ecological conditions in the coastal environment, and the development and implementation of educational curricula and database systems for educators, managers and researchers. In examining the technology available for monitoring the environment and observing physical and biological processes, a number of papers focused on remote sensing instrumentation for aerial photography, current and future radar systems on Earth resource satellites, multispectral scanner systems on board the United States Landsat, the Japanese MOS-1, and the French SPOT satellites, and monitoring devices on board meteorological satellites including the United States National Oceanic and Atmospheric Administration (NOAA) series, the European Space Agency (ESA) Meteosat series, the Soviet Union Meteor series. This publication also includes various satellite-assisted technologies that can provide services and information that are essential for the social and economic development of a country. In particular, a review is presented of the new and evolving hardware and software technologies in the communications and computer field that can assist rural education and health programmes as well as disaster relief efforts. Because the papers are selected from workshops, training courses and seminars held in various parts of the world, they addressed remote sensing and satellite communications issues that correspond to the particular needs of the regions concerned.

This publication is the second in the series of annual United Nations publications initiated in 1989 and dedicated to different fields of space technology applications. These publications aim to promote further international exchange of information and experience as well as disseminate information on United Nations activities in assisting developing countries to utilize space technologies for their social and economic development. They also constitute a contribution of the United Nations toward ensuring that the peaceful use of outer space is carried out for the benefit and in the interest of all countries.

V Safronchuk
Vasiliy S. Safronchuk
Under-Secretary-General for
Political and Security Council Affairs

CONTENTS

Page

Foreword.. iii

Selected papers

Application of Remote Sensing in Agriculture
P. O. Adeniyi.. 1

Trends in Remote Sensing: How Will These Affect Third World Research and Practice?
W. Bie... 23

Planning and Management of Remote Sensing Projects
M. Hedlin.. 29

Combination of Field Data and Remote Sensing Data
H. Olsson.. 35

Operational Use of Radar Images: From Airborne to Spaceborne Missions
J. F. Dallemand and J. Lichtenegger.............................. 47

Microwave Applications For Weather, Climate and Hydrology
E. T. Engman... 53

Data Acquisition and Flight Planning for Agricultural Applications
C. A. Hutton and K. F. Link...................................... 79

A Review of Radar Remote Sensing for Tropical Forest Management
R. K. Raney, F. J. Ahern, R. V. Dams, and D. Werle.............. 87

Remote Sensing and Geographic Information System Training Requirements in Arctic Canada
H. Epp and B. B. Rigby... 107

Remote Sensing for Agricultural Development
Z. D. Kalensky... 115

Communications Technologies for Development
L. A. Bransford.. 125

A Rural Communications Network for Health Care Delivery
M. House... 139

Page

Design, Implementation and Access via Satellite to Telecommunications Statistical Databases on Microcomputers
B. Humm.. 145

Satellite Communications and Disaster Relief
J. Kraml.. 161

APPLICATION OF REMOTE SENSING IN AGRICULTURE*

Peter O. Adeniyi
Laboratory for Cartography and Remote Sensing
Department of Geography
University of Lagos
Lagos, Nigeria

INTRODUCTION

In Africa, as in many other parts of the world, agriculture is a vital component of the resource domain and it has continued to be a key element in the development process. Consequently, agriculture has been the subject of a number of innovations such as farm settlement schemes, the introduction of mixed farming, new seed varieties and fertilizers, and more recently the establishment of large-scale irrigation projects. Despite these efforts, the continent, which was a net exporter of food only 25 years ago, is now a growing net importer of food.

Although this state of affairs has been influenced by the rapid population growth of about 15 million every year and the incidence of global climatic change over the past 20 years, the poor performance of agriculture has been exacerbated largely by the inadequacy of timely spatial data on biophysical, economic and social variables. Consequently, these variables have been weakly integrated into the agricultural planning and development process.

The planning and development of agriculture require a variety of information ranging from generalised land use information to very specific information such as the type and location of certain insects and/or diseases affecting certain crops. In this context, the implementation of agricultural management decisions would require diverse data on a variety of agricultural components. Among such data are the following:

(a) Land use and land use change over space and time; (b) Total cropping; (c) Crop types; (d) Crop yield, (e) Crop moisture requirement; (f) Agricultural population, (g) Farm plots/family, (h) Type of farm and farm sizes (i) Soil characteristics (including soil erosion); (j) Soil suitability/capability, (k) Total rangeland, (l) Range carrying capacity, (m) Livestock population; and (n) Climatic information (e. g. rainfall, temperature, wind speed and evapotranspiration).

These and other socio-economic data are basically required for the proper planning and prudent management of agricultural land resources.

---

* This paper, which was presented at the United Nations Training Course on Remote Sensing Education for Educators, organized in co-operation with the Government of Sweden, Stockholm and Kiruna, Sweden, 14 May to 15 June 1990, does not necessarily reflect the views of the United Nations.

Although several infrequent attempts have been made by public and private institutions as well as individuals to generate information on a number of agricultural components listed above through ground-based surveys, census records, mailed questionnaires and field interviews, such surveys have not only been spatially deficient and temporally inconsistent, they are costly in terms of time, labour and organization. These limitations are further compounded by poor infrastructural facilities, poor institutional arrangements and the "unavailability" of the contemporary technology such as remote sensing.

During the last two decades, however, the application of remote sensing technology in industrialised and several developing countries has shown that many of the basic agricultural data requirements in Africa can be met by the application of this technology. The justification for this conclusion is based on the advantage of this contemporary technology. These advantages include:

(a) The agricultural landscape and most remote sensors depend upon the sun for energy, thus making the former more readily exposed for the recording capacity of the sensors.

(b) The synoptic view afforded by remotely sensed data not only allows the integrated view of the agricultural landscape in a consistent manner, it also makes the study of inaccessible areas possible. Furthermore, the coverage facilitates a more complete sample of an entire area, thereby eliminating the usual biases of ground based studies.

(c) Once an image of a place has been acquired, such an image provides a permanent record of the landscape for that time and a base data from which further agricultural land use change can be evaluated.

(d) The temporal resolution of remote sensing data, that is, the potential to obtain remote sensing data to meet the temporal requirement of a given agricultural objective, is highly superior to ground-based systems.

(e) Rapid and consistent information extraction. The capability of human/machine interaction with remote sensing data has increased the rate at which desired information can be extracted in a consistent manner. This capability has been made possible because most satellite remote sensing data are acquired in digital form.

(f) Remote sensing data are recorded in formats that facilitate multidisciplinary application of knowledge in the most convenient manner. This single attribute is more responsive to the multi-layered agricultural data requirement.

(g) The combined effect of the above advantages has made remote sensing comparatively more cost-effective than the conventional methods.

These and other advantages of remote sensing have led to its being used for the detection, identification, classification, measurement and monitoring of agricultural phenomena. The general and specific areas of application are listed in Table 1. This paper will focus on the following areas:

- Agricultural land use mapping;
- Crop identification and inventory;
- Soil survey; and
- A very brief note on agro-climatology.

Before examining how remote sensing is applied in the above areas, a brief overview of image interpretation tasks and strategies as well as other related issues, is first undertaken.

IMAGE INTERPRETATION TASKS

The extraction of information from remotely sensed data involves several tasks, some of which may not be undertaken for the accomplishment of a given objective. These tasks include: (a) classification; (b) enumeration; (c) measurement; and (d) delineation. Each task is briefly described below.

Classification

The task of classification involves the assignment of objects, features or areas to an already established "informational class". The assignment takes place after the objects, features or areas have been adequately identified by the image interpreter. The identification of the objects, features or areas, in turn, depends on the logical application of image elements such as tone or colour, texture (apparent roughness or smoothness of an image), pattern, shape, size, shadow and site. These image elements are complemented by the interpreter's knowledge of the area under investigation.

This task is a fundamental requirement for inventory of resources such as land use/land cover. The essence of a classification scheme is really to give names to various land use and land cover types. A classification scheme is therefore developed on the basis of the peculiarities of a place, the attributes of the object of investigation and the purpose to be served by the output products. While a classification scheme should be comprehensive, each land use and land cover should be clearly defined so as to enhance replicable and repetitive results over space and time. Such a condition is necessary for comparative and change detection purposes.

TABLE 1

Possible Areas of Applications of Remote Sensing Techniques In Agricultural Surveys*

A. Areas of General Applications:

agricultural land-use mapping
agricultural land-use change
agricultural population distribution
land-use potential
agrometeorology
rural transportation network
soil surveys
water resource surveys

B. Areas of Specific Application:

1. Applicable to Crop Surveys:

- crop identification
- crop acreage
- crop vigor
- crop density
- crop maturing
- growth rates
- yield forecasting
- actual yield estimates
- planting dates
- harvesting dates
- soil fertility
- areas of fertilizer application
- effects of fertilizers
- soil toxicity
- soil moisture
- excessive salinity
- water quality
- irrigation requirements
- irrigation effectiveness
- drought prediction
- weed concentrations
- nematode infestations
- insect infestations
- disease infestations
- location of disease-resistant species
- frost damage
- storm warning
- flood warning
- fire surveillance
- fire control
- assessment
- water availability
- location of canals
- detection of heat in silos, etc.
- food and early warning system (FEWS)

2. Applicable to Range Surveys:

- forage-species identification
- delineation of forest types
- condition of range
- carrying capacity
- forage yield
- growth rates
- times of seasonal change
- development potential
- location of water
- water quality
- drought prediction
- extent of erosion
- identification of toxic species
- soil fertility
- soil moisture
- weed infestation
- insect infestations
- disease infestations
- wild-life inventory
- effects of wild-life
- rodent damage
- fire surveillance
- fire control
- trafficability
- conditions of fences

3. Applicable to Livestock Surveys:

- cattle population
- sheep population
- pig population
- poultry population
- distribution of animals
- animal behaviour
- disease identification
- types of farm buildings

---

*Adapted with minor modifications.

To establish an adaptable classification, a multilevel scheme is often preferred. This hierarchical system has the potential capability to accommodate mixed concepts. In this system, classes at higher levels can be collapsed to form fewer classes at the lower levels (see table 2). This system of classification is highly flexible and suitable for the application of remote sensing.

TABLE 2

A SAMPLE OF A MULTI-LEVEL CLASSIFICATION SYSTEM

Level I	Level II	Level III
100 built-up areas	210 cropland	211 row crops
200 agriculture	220 orchards	212 field crops, etc.
300 rangeland	230 tree crops	
400 forest land	240 confined feeding operations	
500 water	250 speciality farms, etc.	
600 wetland		
700 barren land		

An important aspect of a classification scheme is the coding system, that is, the system of labelling the classes during the mapping process. Three coding systems which are commonly used are: (a) alphabetic codes, that is, the use of alphabets to represent a particular class (e.g. c for Cropland); (b) alphanumeric codes, that is the combined use of alphabets and numerals (e.g. C1 for row crops and C2 for field crops); and (c) numeric codes, that is the use of numerals to represent classes. The numeric coding system (as in table 2) is more flexible and has the potential to accommodate as many classes as desired.

Enumeration

This task involves the counting of discrete objects on an image. This task is achieved after the objects have been properly identified. For instance, one may wish to count the number of rural settlements, lakes, hand-dug wells, etc. If the location of the objects is not required, this task may be accomplished directly on the image. Where the location and pattern of distribution of the objects are important, the objects may be mapped and the counting may then be accomplished on the mapped output product.

Measurement

Two broad types of measurements can be undertaken. The first relates to height, distance, volumes and area. Precise measurement of this type forms the central core of the field of photogrammetry. For visual image analysis as applied to land use/land cover mapping, this task, especially area measurement, is normally carried out on the output map products.

The second type of measurement involves the quantitative evaluation of image brightness. When this type of measurement is carried out on the imagery acquired within the photographic portion (visible and near infrared) of the electromagnetic spectrum (EMS), it is called photometry; otherwise, it is called radiometry. An instrument called a densitometer is normally used for this type of measurement. This type of measurement forms part of the technique being used in crop yield estimate.

Delineation

This task involves the drawing of boundary lines around objects or areas that have been adequately identified and classified into an appropriate "information class". In land use/land cover mapping, for instance, this task is very crucial because the accuracy of the final map product and area calculation depend on how this task is accomplished. It requires judgemental decisions based on convergence of evidence and the systematic application of the minimum area recording unit. The more complex an environment is, the greater the difficulty of accomplishing this task. Thus the age-old problem of "where to draw the line" is really an important task in image interpretation.

IMAGE INTERPRETATION STRATEGIES

An image interpretation strategy consists of a set of logical and systematic procedures which an interpreter employs to enhance his capability to relate spatial patterns on the ground to their appearances on an image. Five of such strategies identified are field observation, direct recognition, interpretation by inference, probabilistic interpretation and deterministic interpretation. Each is briefly explained.

Field Observation

Field observation is an important strategy for image interpretation, particularly when the interpreter cannot adequately relate the image to ground conditions. Under this situation, the interpreter must make a preliminary field observation to ascertain how the ground conditions appear on the image. As much as possible, the field observation should take place shortly after imagery acquisition, otherwise the image appearance may be different from the ground conditions. For this purpose, the imagery must be taken to the field to permit the development of image interpretation keys. Another form of field observation which plays an indirect role is the field verification of interpretation results. This is carried out to determine the accuracy of the interpretation. In the context of image interpretation strategy, it is the field observation carried out prior to actual image interpretation that is relevant here.

Direct Identification

This involves the application of the interpreter's knowledge about the image elements (tone/colour, texture, pattern, shadow, size, shape, site and association) and how those image elements correlate with the desired informational classes. This strategy, when applied to visual image analysis, is highly qualitative and it requires logical and systematic examination of the image elements. There are situations where an object can be identified directly on the basis of one single element. In other circumstances, direct identification of an object may require the combined use of several image elements. However, the smaller the scale of an imagery, the greater the reliance on tone and/or colour for direct interpretation of objects. For visual analysis of land use/land cover on remotely sensed data, this strategy is greatly relied upon.

Interpretation Inference

This strategy involves the use of visible objects on imagery for the identification of objects that are not so directly visible on the imagery. The visible object used for the identification of the less visible object is referred to as a surrogate or proxy. Thus, this strategy is often referred to serve as an indirect, proximate or surrogate method of interpretation. This strategy is commonly applied in soil surveys. Due to the fact that the soils are often closely related to vegetation and land forms (which are generally visible on imagery) they are often used as surrogates for the mapping of soils (which are often not directly visible on imagery). The accuracy of this interpretation strategy depends largely on the understanding of the relationship between the surrogate and the object being mapped.

Probabilistic Interpretation

This strategy involves the combined use of image and non-image data and quantitative classification algorithms. For instance, certain soil types may be known to be suitable for the growth of a particular crop. The knowledge of the locations of that soil type may lead to a decision rule expressing the probability of finding the crop on those locations as 0.85 and only 0.10 probability of finding the crop on another soil type.

Similarly, this strategy can be applied to crop identification, if information on crop calendar is available. For instance, if it is known that late millet is harvested in November, the probability of the presence of millet on a February image would be very low. Given this knowledge, the interpreter would not have to spend time looking for millet on the imagery or making the mistake of classifying dry season maize for millet.

Deterministic Interpretation

This strategy is based upon quantitatively expressed relationships between image characteristics (such as height of objects). In this strategy, non-image information is rarely employed. The strategy is commonly applied in the field of photogrammetry.

With respect to image interpretation, the strategy is often applied by measuring the image brightness and correlating this with specific informational class. Unsupervised digital classification is based on this strategy.

SOME BASIC ISSUES IN THE USE OF REMOTE SENSING IN AGRICULTURE

It has been rightly argued that the application of remotely sensed data for detection, identification, classification, measurement and monitoring of agricultural phenomena is based on the assumption that agricultural features have consistent identity on a given type, or types, of remotely sensing imagery. These agricultural features include: crop type; crop density; crop height; crop geometry; crop vigour; crop moisture; soil type; soil moisture; soil temperature; size of farm; farm layout; tillage; irrigation and harvesting practices; type and size of livestock and many other agronomic practices. The spatial and temporal variations of these agricultural features require the consideration of the type of sensors that can be used for the accomplishment of a given agricultural problem.

Thus, in planning the use of remote sensing for agricultural projects, the following issues must first be considered:

- Image characteristics (such as tone/colour, texture, shape, shadow, pattern etc);
- Image resolution;
- Image scale; and
- Choice of imagery and imagery acquisition period.

The last issue is briefly described.

Choice of Imagery and Imagery Acquisition Period

Due to the fact that different agricultural features exhibit varying energy returns in various portions of the electromagnetic spectrum (EMS) and because the energy returns, in turn, vary with the phenological cycle of the agricultural features, the choice of imagery and when to acquire it are basic considerations in the application of remote sensing for agricultural projects.

The choice of imagery is influenced by a number of factors which normally include:

- The objective of a given project;
- The environmental setting of the project area; and
- The agricultural management practices in the area.

Other considerations include availability of appropriate interpretation equipment and cost.

Until quite recently, the choice of imagery has been limited to photographic sensors (black and white, colour and colour infrared aerial photographs). This choice has now been extended to other forms of remote sensing systems such as passive and active microwave systems, and various satellite-based multispectral scanner systems. Given the availability of all these systems for a given project, the problem of a particular choice may be compromised by the integrated use of all of them.

Having decided on the choice of imagery, the next step is the determination of the most appropriate period for the imagery acquisition. The determination of the imagery acquisition period requires the knowledge of climate and agricultural calender.

Climatic information, especially rainfall and regional agricultural calender are required to provide information about agricultural activities such as the land clearing, planting, weeding and harvesting season. Historical, rather than yearly climatic data is required in regions with climatic variations. Equally important is the knowledge about how the farmers adjust to the climatic variations.

Apart from the knowledge of agricultural seasons, climatic information is also necessary for the determination of the periods with less atmospheric attenuations such as haze, dust and cloud. These atmospheric phenomena may inhibit the extraction of the desired information even when the imagery is acquired at the most appropriate period. In practical terms, it is the combination of crop calender, climatic information and the knowledge of atmospheric attenuations that is often used to determine the period of imagery acquisition.

AGRICULTURAL LAND USE MAPPING

The term land use has not been easy to define in a manner that makes its meaning clear in all contexts. This difficulty arises from the complex relationship that exists between the land and the users. While land is spatially complex in terms of structure, composition and form, its uses, especially with regard to agriculture, are more complex. The human use of the land represents the sum total of the attitudinal and perceptual responses of individuals and institutions.

Broadly, therefore, land use represents the imprint of people's activities on, and in relation to the land. It is to a large extent an abstraction which is not always directly observable by even the closest inspection. What is commonly seen is the physical artifacts of a use. It is largely for this reason that the term "land cover" is often used together with land use even when the objective of the mapping concerns the latter.

Land cover, in turn, refers to the vegetational and other natural phenomena and artificial constructions covering the Earth's surface. Thus, while land use is abstract, land cover is concrete and because remote sensors normally and essentially record information about all the phenomena that cover a given area, the image interpreter only uses his knowledge of image elements and the imaged area to give a particular 'use' name to a particular identified 'cover'.

The use of land use/land cover even when the main objective of the mapping is on agriculture is necessitated by the fact that some phenomena that cover the land surface, for instance, forest, may not be easily associated with several of its various uses such as timber production, hunting and recreation. On the other hand, the presence of grass cover is not necessarily an indication of pastoral activities.

From the above, it follows that agricultural land use mapping is a component of land use and land cover mapping for which all forms of remote sensing systems have been used. When the objective of land use/land cover mapping is essentially on agriculture, considerable emphasis is placed on the imagery acquisition period. Thus, while our interest in this lecture is on agricultural land use mapping, the same approach being used for mapping land use/land cover is adopted. Land use/land cover mapping can be carried out either through visual image analysis, or digital image processing or through the combination of visual and digital image analysis. The choice of analysis depends on the type of available imagery. For instance, before the advent of digital multispectral scanner data in the early 1970's, land use/land cover mapping was largely based on the visual interpretation of photographic sensor products. This method which has been extended to other remote sensing systems, is briefly outlined.

Visual Image Analysis Procedures In Land Use Mapping

The following steps are involved:

(a) Clear statement of objective. Although the general nature of the mapping is known - such as agricultural land use mapping- it is necessary for the interpreter to confer with the envisaged user of the mapping product. This information will assist the interpreter in making the decision about the type of imagery to use and the level of classification (detail) required.

(b) Imagery acquisition which must be determined according to the central objective of the mapping and in line with the issues presented in the above section.

(c) Preliminary field observation and collection of relevant collateral material.

(d) Development of appropriate classification scheme (as already presented).

(e) Creation of a plotting base map. Due to the fact that the most important output product of the mapping is a thematic map showing the spatial distribution of various agricultural land use types, there is a need to construct a planimetric plotting base. Such a plotting base (or overlay) is constructed for the positional accuracy of each land use polygon as well as a locational guide for the recording of the interpreted land use.

In constructing a plotting base for land use and land cover mapping, for instance, the choice of map projection is very important. Due to the fact that land use and land cover information is essentially based on area data, equal area projection, which ensures that the size of a unit area in one part of a project area is equal in size to a similar area in another part of the project area, is normally desired. A good plotting base is also required if the output map product is to serve as a base for future land use change studies.

The most commonly used plotting base is topographic maps. Where they are not available, other types of maps or rectified mosaic may be used. However, rectified mosaics are very expensive to construct and they lack some vital information such as place names and administrative boundaries.

(f) Determination of the Minimum Area Recording Unit (MARU). In mapping land use and land cover based on remotely sensed data, it is important, prior to image interpretation, to determine the MARU. MARU refers to the minimum areal extent of land use and land cover type that can be manually delineated and coded on the recording base.

The determination of MARU is often based on a number of factors, which include the following:

- the scale and resolution of the imagery;
- the scale of the recording base and the final map product; and
- the environmental complexity of the area under study.

The idea of MARU is to avoid unnecessary waste of interpretation time as well as the reduction of "noise" in the final output map.

Cartographically, it is difficult to delineate and code any map area smaller than about 2.54mm on a side. At a scale of 1;100,000, a MARU of 4mm^2 has been suggested. This rule, however, may not be applied to all classes of land use and land cover if some classes of interest settlements or small bodies of water are very important to the objective of the mapping. In such cases, different shading may be used instead of codes.

(g) Implementation of appropriate image interpretation tasks and strategies as reviewed in image interpretation tasks described above. For visual image interpretation, various optical equipment can be used. This step is very critical because it involves the identification of the land use types as defined in the classification as well as the delineation of the boundary polygon for each land use type. Apart from using the image elements, the interpreter must complement them by the use of collateral materials. The combined application of direct, indirect and probabilistic interpretation strategies is very essential. However, the image interpretation strategies should not be applied globally. Because of variations in land forms, soils and moisture regime, all of which influence the agricultural landscape, the project area should first be sub-divided into landscape units. This step is necessary in order to avoid interpretation errors caused by variations in landforms, soils, moisture regime and other environmental factors leading to the same agricultural features appearing differently on the imagery (e.g. floodplain rice and upland rice will appear differently on the imagery). For each landscape a photo-interpretation key based on the preliminary field investigation may be developed to assist in the interpretation process.

Each land use identified and properly delineated on the plotting base must immediately be assigned a label (e.g. alphabetic, alphanumeric or numeric codes). In situations where different land uses which are contigously located are too small in area to be separately delineated on the plotting base (i.e., not meeting MARU), the different land uses should be given a name that will describe this situation, for example, "mosaic of cropland and pasture".

(h) Production of preliminary land use map. The result of visual interpretation step is regarded as a preliminary land use map simply because it has not been cross-checked for accuracy in the field. Also, in the process of carrying out that step, certain problem areas may be marked for field complection.

(i) Field verification. These steps involve the checking of the preliminary land use map in the field. The paper print of the preliminary map and the imagery are normally taken to the field. The field verification must be carried out in a systematic manner and should be done to cover each land use type. The various field sampling techniques are used for the verification. Normally, the field verification involves:

(i) the checking of the interpretation accuracy; and

(ii) the checking of the individual land use boundaries. In the field of agriculture, the field verification should be conducted within the agricultural year, otherwise the boundaries of land uses found on the ground may be different from those appearing on the image. Because this condition is often very difficult to meet, adequate care must be taken in checking the interpretation results.

(j) Post-field interpretation. It is often necessary to carry out post-field interpretation in order not to introduce errors arising from the integration of field results.

(k) Production of final land use map. This is basically a cartographic exercise. However, it requires proper editing to ensure that all polygons are closed and each labelled.

(l) Statistical generation. This is done by calculating the area of each land use type. Instruments such as the digital planimeter are used for the area calculation.

The visual image interpretation procedure outlined above has been applied on various remotely sensed data in nearly all parts of the world. Variation in the procedure is mainly associated with the objective of each mapping and the peculiarities of each place. However, in many situations, a single date imagery may not reflect the true position of the agricultural landscape in the area. This is particularly so when a piece of land is used for different agricultural purposes during each season of the year or when the climatic situation restricts the use of some areas for agricultural purposes during parts of a year. Thus, to have a comprehensive agricultural land use information, multi-temporal images are often desired. This consideration has led to the increasing use of satellite remote sensing imagery in agricultural land use mapping. Although resolution of the Landsat multispectral scanner (MSS) is rather coarse for detailed mapping of the traditional African agricultural systems, Landsat Thematic Mapper (TM) and the Satellite Probataire Pour L'Observation de la Terre (SPOT), High Resolution Visible (HRV) images have been found useful for medium scale mapping of African agricultural land use patterns.

Digital Approach to Agricultural Land Use Mapping

Several of the steps discussed under the visual approach to land use mapping are equally applicable to digital methods. Digital image analysis actually started in early 1970's at the advent of Landsat 1. Unlike the visual approach, which is applied to photographic products of all forms of remote sensing, the digital approach is only applied to numerical image data which are normally recorded on computer tapes. Thus, the digital approach is highly instrumental dependent and it requires some knowledge of computer science. Two basic digital techniques which are generally applied to resource mapping are:

(a) Unsupervised classification; and

(b) Supervised classification.

Each is briefly discussed.

Unsupervised Classification Technique

This technique is based on the computer manipulation of the brightness value (BV) or the digital number (DN) of the pixels within the imaged area of interest. The BVs or DNs are automatically classified into the number of categories dictated by the analyst. The result of this method yields "spectral classes". They are so called because the classes created are solely based on spectral information. The output of this technique must be taken to the field to ascertain the degree to which the "spectral classes" correlate with the desired "informational classes".

This technique has been extensively employed to map land use/land cover. In so many cases, some of the "spectral classes" have been found to correlate very well with the desired information classes. Such results, however, have been obtained in areas where farm plots are large and planted with single crops. In areas where farm sizes are small with different crops planted on them, this technique has largely failed. For instance, in our study of the Sokoto-Rima Basin in northwestern Nigeria, we found that wild rice, grasses and low shrubs are classified together with rice fields. Also, by applying this technique on Landsat (TM) in the Axias Alluvial Plain (Greece), it was found that both rice and forest are grouped into one class. However, an accuracy of 75 per cent was achieved for both non-irrigated (wheat) and irrigated land.

Supervised Classification Technique

The supervised classification technique is based on the same concept as the unsupervised classification technique. The main difference is that the analyst is more involved in the selection of the pixels whose digital numbers are then used to generate the statistical parameters for the classification process. In applying this technique, therefore, there must be already established "informational classes", that is, categories of agricultural land uses that can be mapped. With the classes established, the analysts must then go to the field (preliminary) to select typical but representative areas within each agricultural land use category of interest. Such selected areas are called "training areas". The selected areas must be capable of being appropriately identifiable on the imagery. Normally, the training areas should be indicated on a map, aerial photographs or paper prints of the image to be digitally processed. In selecting the training areas, the bio-physical factors must be taken into consideration. For instance, if millet is grown in a floodplain and in an upland area, training areas must be selected in both areas. This is necessary to neutralize the effects of differential ecological conditions in both areas. Alternatively, the project area could be divided into physiographic units and each unit separately treated. The statistical parameters generated on the basis of the training areas are then used to classify the whole of the project area.

There are different versions of this technique but the most commonly used is called "maximum likelihood" classification. This technique has been extensively used for agricultural land use mapping. Its results are superior to that of unsupervised classification technique. However, because the technique largely relies on the spectral information, misclassification of agricultural land use does exist. Although the problems associated with this technique, especially with respect to agricultural land use mapping are partly caused by the resolution factor and the power of the algorithm, the major problem relates to the agricultural management practices and the environmental complexity of a given location. For instance, accuracy of 85 per cent of the Axias Allurial Plain was achieved in mapping rice fields. Also, the accuracy of irrigated cropland was increased from 75 per cent to 85 per cent. However in our study of Sokoto-Rima Basin, it was not possible for us to uniquely classify traditional rice fields. The results of this technique, when applied to Landsat TM and SPOT HRV, are far better than the results obtained on Landsat MSS.

Combined Visual and Digital Mapping Techniques

The major problem of the visual analysis procedure is the delineation of the boundaries separating different land use types. On the other hand, the digital classification procedure relies heavily on the spectral information. Since in visual analysis several image elements and non-image elements are used, the emerging "hybrid" procedure is to use the computer to enhance the imagery, which is then visually interpreted. Various enhancements, which will be discussed later in this course, have been developed. We have found that the use of enhanced Landsat MSS imagery (bands 4, 7 and VI) provided far superior results than the unenhanced Landsat MSS-False Colour Composite (FCC). Apart from increasing interpretation capability, the boundaries of different land uses are more sharply defined on the enhanced Landsat MSS-FCC.

Finally, while visual and digital procedures are being used for land use/land cover mapping, the trend now is the combination of the two procedures.

CROP IDENTIFICATION AND INVENTORY

Perhaps no aspect of remote sensing applications in agriculture has received greater attention than crop identification and inventory. The reason for this interest derives from the utility of the information. For instance, crop identification and inventory allow for crop area estimation, which in turn serves as an important input to crop yield estimate and yield forecast. It is also used for the recognition of crop stress and crop diseases. The recent effort on the food and early warning (FEW) system is largely based on the identification and inventory of food crops.

Unlike agricultural land use mapping, which at the national and regional scale aggregates the agricultural uses of the land, crop identification focuses on the mapping of individual crops. While the agricultural land use map serves as a basic operational input in crop identification, the factors which influence the ability to identify crops on remotely sensed data as well as the techniques of identification are more complex than those required for land use mapping. One important factor in the identification of crops on remotely sensed data is the timing of imagery acquisition, that is, the time when maximum discrimination among crops can be achieved. This requires accurate knowledge of crop calendar and the growth rate pattern of each crop.

Various methods have been, and are being, developed for the identification of crops on both single date and multidate imagery. Also, all forms of remote sensing data have been tested for the identification of various crops. A very brief outline of some of the methods is presented below.

Identification of Crops on Aerial Photographs

Various types of aerial photographs - black and white, colour and colour infrared and multiband photographs - have been, and are being, used for the identification. The initial effort to identify crops started with low to medium altitude aerial photographs. The stereo-viewing capability, which provides stereo-height information and the high spatial resolution of the photographs, are the major diagnostic factors. Using crop height as a variable for the identification of crops means that the photographs must be acquired when the crops have attained reasonable heights for discrimination. Both single date and multidate photographs have been used. Using sequential aerial photographs acquired at scale 1:12,000 in Switzerland, the size, shape, and boundaries of crop field could be best determined in May and August, while individual crops were easiest to discriminate in June and July. On the other hand, it was found that stereoscopic height is an important discriminant of crops in Switzerland. It has also been noted that the use of multidate photographs acquired during the growing season improves crop identification. Apart from height information, other factors which influence the identification of crops on aerial photographs include crop spacing-ridge spacing, shape of farm plots, planting of single crop on individual farm plots, crop density, farm layout, etc. Thus, in tropical countries, the identification of crops using the above criteria has not been very successful because of the spatial disorder of agricultural lands. In fact, attempts to identify tree crops such as coca, coffee and kola-nut has not been successful except for those grown on large plantations. The reason is these crops are largely grown under natural trees and their boundaries are ill defined.

On smaller-scale aerial and space photographs, heavy reliance is placed on the tone or colour for crop identification. The results of the studies carried out on high altitude and space photographs in Phoenix, Arizona and Imperial valley, United States showed that colour SR photographs are good for crop discrimination.

Use of Satellite Multispectral Scanner Data For Identification

The result of the densitometric measurement carried out on aerial photography and the increased possibility of obtaining multitemporal satellite data led to the investigation of the spectral responses of crops on multispectral images. Several quantitative techniques based on the integration of image and non-image elements have been developed. The investigations range from the use of an individual band to a combination of many bands and a variety of image enhancement techniques. Other investigators have devoted attention on crop canopy and crop-soil relationship, while others investigate the suitability of vegetation indices and various digital classification procedures.

A major effort at identifying crops on satellite imagery was initiated shortly after Landsat-1 became available in 1972. This experimental research - Crop Identification Technology Assessment for Remote Sensing (CITARS) - was designed for automatic identification of crops. This experimental research was conducted between April, 1973 and April, 1975 by the Earth Observation Division (EOD) of the National Aeronautics and Space Administration (NASA) Johnson Space Centre, the Environmental Research Institute of Michigan (ERIM), the Laboratory for Applications of Remote Sensing (LARS) of Purdue University and the Agricultural Stabilization and Conservation Service (ASCS) of the United States Department of Agriculture (USDA). Corn and soya beans were assessed in six sites in Illinois and Indiana, United States. Landsat-1 digital data were acquired throughout the growing season in 1973. The objectives of the CITARS experiment were:

(a) To assess the effects of Landsat data acquisition during the corn and soya bean growing season on crop identification performance;

(b) To assess the effects of differing geographic locations having differing soils, weather, management practices, crop distributions, and field sizes on crop identification performance;

(c) To quantify the variation in crop-identification performance using the differing automatic data processing classification procedures;

(d) To test the ability to extend training signatures, selected within a test area, to train the classifiers in other areas; and

(e) To assess crop identification benefits to be derived from classifying with multiple Landsat data acquired multi-temporally during the crop growing season.

The major conclusions of this important experiment are as follows:

(a) That crop-identification performance for corn and soya beans varied throughout the growing season with pure pixel-classification accuracy being maximum in late August;

(b) That the probability of correct classification of pure pixels was not well correlated with, and thus was not a reliable indicator of, proportion- estimation performance;

(c) That proportion-estimation accuracy was strongly correlated with both average field size and the proportion of major crops in the segment, but pure pixel-classification accuracy was not. Mixtures of pixels containing two or more cover types were determined to be major contributors to the bias in proportion estimates;

(d) That the manner in which ground cover classes were selected and used to train the classifier strongly influenced the amount of bias in proportion estimates;

(e) That probability of classification and proportion estimation accuracy both were decreased when training statistics developed for a different location or date were used;

(f) That a mean level adjustment algorithm for first order adjustments to training statistics used for non-local classifications increased the probability of correct classification of pure pixels, but did not improve proportion estimates for whole areas; and

(g) That the use of multi-date data improved both proportion estimation accuracy and probability of correct classification.

Following the initial results of CITARS and the increasing need for accurate forecast of food crops, especially wheat, a joint research effort on Large Area Crop Inventory Experiment (LACIE) was initiated by NASA, USDA and National Oceanic Atmospheric Administration (NOAA) in 1974. The experiment, which first covered nine States in the United States, was extended to Canada, the Soviet Union, India, China, Australia, Argentina and Brazil. The system developed and evaluated for crop forecast used Landsat MSS data to identify crops and their hectarage and the global weather data from the World Health Organization (WHO) ground network to forecast yield for harvested hectares. The experiment was based on a per cent sample.

The accuracy of the LACIE met the set performance goals. For instance, the 1977 LACIE wheat production final estimate for the Soviet Union was 91.4 million metric tons, which compared very well with the official USSR figure of 92 million metric tons.

Following the achievement of CITARS and LACIE another programme on Agriculture and Resources Inventory Survey through Aerospace Remote Sensing

(AgRISTARS) aimed at automated information extraction techniques for non-United States crop was initiated.

The results of these studies have led to the increasing use of Landsat MSS and now Landsat TM and SPOT HRV. With the latter two, better results have been obtained. In all the cases, the ability to identify crops depends largely on the complexity of a given environment and the agricultural practices. While most studies have achieved appreciable accuracy on mono-cultural crops, similar successes have not been achieved on mixed crop lands.

Identification on Radar Imagery

Due to the fact that time of imagery acquisition is very important for crop identification, the cloud-penetrating capability of radar has been employed especially in areas which have persistent cloud covers. Several studies have been conducted, especially in North America, with a K-band multiple polarization radar in a test area near Garden City, Kansas and with X-band. Evaluating these radar data for crop type, crop cover, crop moisture and other parameters, the following results were obtained:

(a) Statistical analysis indicates that the type of crop is the most important variable influencing radar return;

(b) Allowing for differences in crop type, other major influences on radar return are crop height, percentage of ground covered by vegetation and row direction (i.e. bare ground and low cover); and

(c) Crop moisture, which shows a weak relationship to radar return.

Although further research efforts have shown that certain crops could be identified under certain conditions, radar imagery is less used for crop identification because other sensing systems provide better results. However, given the problem of cloud and other atmospheric conditions in the Tropics, the potential of radar data, if properly investigated, is really great.

SOIL SURVEYS

The knowledge of soils and their characteristics is very vital for agricultural planning and development. Soils are generally complex in structure and composition. Scientifically, the chemical and physical properties of soils relative to their soil-farming factors, such as parent materials, relief and climate, are understood. Although different soils can be identified in situ and through laboratory analysis by their colour, mineral content, organic matter, particle size, texture, structure and surface roughness, etc., the application of remote sensing in soil surveys is based on the understanding of how these and other variables respond to reflected and emitted radiation.

Apart from arid and semi-arid soils which are largely directly exposed to the sun's energy, and therefore capable of direct identification on remotely sensed imagery, soils in other ecosystems are usually covered by vegetation.

Consequently, the identification and subsequent mapping of soils on remotely sensed data is largely based on an indirect method. This method is based on the understanding of the close relationship between landform, drainage and vegetation, on the one hand, and soils on the other. Fortunately, landforms, drainage and vegetation can be directly interpreted on remote sensing imagery. This indirect method of interpretation is normally applied through visual image analysis. The method has been applied virtually on all forms of remote sensing imagery. The general procedure is as follows:

(a) Physiographic or land type mapping. This method is based on the assumption that soil pattern has a high correlation with physiography or land types. "Land type" is defined as "an area within a certain climatic range, made up of a distinct association of geogenetically related forms and originating in a certain time span". The boundaries of different land types are interpreted and delineated on the plotting base. When using aerial photographs, it is often necessary to construct a mosaic in order to obtain a regional overview of the physiography. This difficulty does not occur on radar and satellite images. The output physiographic map or land type map is normally taken to the field, first,to verify the correctness of the delineated boundaries, and second, to take soil samples in each of the land types mapped. The analysis of the soils in the laboratory is then used to characterise the soils.

(b) Drainage pattern analysis involves the same procedure as above. Drainage channels are mapped on the imagery, and since drainage pattern has close relationship with soils, this analysis is used together with field and laboratory analysis to classify the soils. Normally, the drainage analysis is often combined with the physiographic information.

(c) Integrated landscape approach. This method combines the first two for composite soil mapping. The manual operation of this technique makes it very time-consuming. However, with Geographic Information System (GIS), this method provides superior results to those of the single-factor approaches.

These approaches have been used on aerial photographs, radar imagery Landsat, MSS and TM, and SPOT HRV for the mapping of several areas in Africa and elsewhere.

Apart from visual interpretation of soils, digital techniques have also been used. These techniques largely involved the manipulation of image spectral characteristics through image classification and enhancement techniques. The results obtained have largely satisfied regional soil classification. The heterogeneity of soils and their varying relationship with other environmental factors which are differentially recorded on remotely sensed data have precluded detailed soil mapping. However, various methods are being developed to adequately calibrate the responses of various soil attributes such as soil moisture, soil organic matter, iron oxide, soil temperature, etc.

An attempt to integrate such factors are being explored through Integrated Land and Watershed Management Information System (ILWIS). A special report on ILWIS was published in the ITC Journal 1988. An ILWIS package has been employed by combining image (aerial photos and multitemporal

Landsat data) and non-image data for soil survey and land evaluation for crop and soil relationship.

AGROMETEOROLOGY

Arising from the incidence of drought which started in the late 1960's and its impact on agricultural production, especially in Africa, the application of satellite remote sensing for the generation of meteorological and climatic information has received considerable support. Various international organizations have established research programmes on the use of satellite remote sensing not only for the generation of basic climate data, especially rainfall, but also for the purposes of monitoring land surfaces changes caused by climatic fluctuations and the agricultural practices.

One of such projects is the International Satellite Land Surface Climatology Project (ISLSCP) which was started in early 1980 (National Program Office, 1985). ISLSCP is engaged in the development of methodologies for the conversion of satellite measurements into estimates of land surface climatological properties such as vegetation cover, albedo, radiation budget, surface temperature and emisivity, soil moisture and precipitation.

In order that meteorological forecasting meets the agricultural needs, an AGRYMET project was initiated in 1975. AGRYMET was formulated to increase food production specifically in the Sahel region. The Food and Agricultural Organization of the United Nations (FAO) has also formulated a comprehensive operational satellite remote sensing based system for monitoring precipitation and vegetation conditions on a continental scale. The system called the Africa Real Time Environmental Monitoring Using Imaging Satellites (ARTEMIS) is based on the use of hourly digital Meteosat data and daily NOAA Advanced Very High Resolution Radiometer (AVHRR) Global Area Coverage data. This system is designed to generate ten day and monthly estimated rainfall maps as well as monthly rainfall anomaly maps for the land area of Africa and the Near East. Derived thematic products will include ten day crop/range land moisture availability maps using the FAO water balance index model and desert locust potential breading activity factor maps as inputs for Early Warning and Desert Locust Plaque Prevention Programmes.

In recognition of the critical role of meteorological and climatic information in various aspects of agricultural activities and the total environment, considerable research efforts have been embarked upon. These efforts concern the use of various satellites in the following areas:

- Radiation budget of the Earth-atmosphere;
- Atmospheric temperature structure;
- Surface radiation studies;
- Cloud classification;
- Rainfall estimation;

- Water vapour analysis;
- Wind field analysis;
- Prediction of severe storms; and
- Weather analysis and forecast.

All these areas have bearing on agriculture, particularly in Africa, where data on all these elements are very scant.

CONCLUSION

Compared with extensive literature on the application of remote sensing in agriculture, this presentation is nothing more than a very generalised overview. However, the little that is covered in this lecture has shown that remote sensing has revolutionised the generation of agricultural information. Those nations that have embraced this technology have not only greatly improved the planning of their national land resources, they have also been able to introduce appropriate management strategies.

The experience of those nations has shown that the opportunities afforded by this technology can only be obtained through committed experimental research activities. In other words, the beneficial application of the technology depends largely on a number of enabling resources such as skilled manpower, availability of imagery and imagery interpretation equipment, local educational and research institutes and, more importantly, supportive local and international institutions. For most of Africa, these enabling resources are lacking. Unfortunately, the African environment and the African management practices do not lend themselves to simple analysis. Thus, considerable effort is required.

TRENDS IN REMOTE SENSING: HOW WILL THESE AFFECT THIRD WORLD RESEARCH AND PRACTICE?*

Stein W. Bie
NORAGRIC
Norway

INTRODUCTION

The last twenty years have added a wide variety of remote sensing tools to the already well-endowed arsenal of aerial photo interpretation, photogrammetry and radar technology. The most surprising aspect of this development has been that the new satelite-based technologies in no way have replaced the well-proven aircraft and ground-based technologies. Highly advanced industrialized countries still routinely produce national coverage of up-dated low and high altitude air photography and make thematic maps based on colour and infrared photography.

The main reasons for this are partly to be found in institutional inertia (and operationality takes priority over new research findings also in industrialized countries) and partly in the superiority in spatial resolution in film and film products over the current generation of electronic space-borne sensors. Yet there is also a more disturbing aspect. We are now all fully aware of the potential offered by new technology. Many of us operating out of technologically advanced countries are most frustrated by colleagues in development assistance organizations who argue against giving priority to remote sensing techniques as part of aid, assistance and cooperation packages. Although their motives may not be questionable (the arguments are often of the appropriate technology-type), the result is exactly equivalent to technological imperialism, where the best technology is reserved for the richest countries. Added to this is the global coverage offered by, for example, satellite imagery, which allows global awareness for the rich of the resources of the poor. Because the poor often have rich resources and the rich have exhausted theirs, this "Peeping Tom" aspect is unpalatable in progressive development assistance. Those who have the greatest problems deserve the best tools. If the technology is deemed inappropriate in a recipient country at a particular time, it is also the duty of the donor community to change the institutional framework so that the best available technology does indeed become appropriate.

This course is clearly a part of that progressive strategy. If, therefore, we can dispose of the paternalistic aspects of the inappropriate technology argument (and urge developing countries to question the argument whenever it appears), we retain both the organizational framework argument and the technology advances argument.

---

* This paper, which was presented at the United Nations Training Course on Remote Sensing Education for Educators, organized in co-operation with the Government of Sweden, Stockholm and Kiruna, Sweden, 14 May to 15 June 1990, does not necessarily reflect the views of the United Nations.

THE ORGANIZATIONAL FRAMEWORK

If there is one thing we have learned in the last 20 years of satellite remote sensing it is that, without a well-founded organizational setting, even the most brilliant bit of technological wizardry will remain with the research scientist and not reach the needy people.

The strength of the traditional air photo interpretation and photogrammetry techniques is that despite their often cumbersome methodologies they have large organizational networks built at the national level in their support. The military and strategic importance of maps has meant that national survey organizations have played significant roles in the planning sector. In many developing countries today national surveys operate efficiently even when other government bodies may be seen to struggle, although there are countries where survey priorities are low.

Mapping emphasis is changing world-wide, from topographic maps, where many countries will have at least rudimentary coverage at 1:250,000 or larger scales, to thematic maps. Development means utilization of inherent natural resources for most poor countries, resources whose location, quantity and quality may not be well known. Traditional survey organizations - with the possible exception of some national geological surveys - have not been geared to thematic mapping. They do not have staff with thematic background nor facilities for interpretation of the varied and multifacetted data that constitute the raw material for resource inventories.

In my view, the prerequisite for resource inventories in developing countries is largely missing. As long as neither the proper organizational framework for thematic mapping nor adequate training facilities for thematic staff exist, the introduction of modern thematic mapping techniques or monitoring services based on, for example, satellite remote sensing, will remain the domain of the expatriate expert community and international consultants. These may of course be extremely competent - they often are - and very devoted to their scientific task, but it should never be the intention of sustainable development that the natural resources of poor nations are better known abroad or by expatriates than by the countries themselves.

For the development of such national capabilities, there is a choice between offering support to national mapping agencies or to universities. It may well be argued that the new technology is sufficiently experimental to remain the domain of the research community, i.e., the universities. Given that universities, also in developing countries, frequently have an easier administrative structure than in the civil service, there may well be instances where industrialized countries initially should target their remote sensing support to the universities rather than to the central organizations of surveys and mapping. Due to the fact that universities also frequently lack the capabilities of routine and operational activities, the longer-term and final receiver will most likely be the survey organization.

HUMAN RESOURCES DEVELOPMENT

Short-term courses may give participants a good overview of alternative sensors, data and processing tools in remote sensing. For operational use, however, deeper insight is required.

The normal human resources development plans include the training of a limited number of highly skilled people in centres of excellence abroad. Problems frequently arise on their return from training at e.g. M.Sc. or Ph.D. levels abroad. Sometimes tasks and equipment are not available that will allow them to continue working in their field of specialization. Equally common is a quick promotion into a more senior post with strong administrative duties, far from the remote sensing task for which she or he has been trained.

Industrialized countries offering training support to developing countries should ensure that the facilities and administrative set-up to which a trainee returns offer reasonable promise of continuation of what the training was meant to initiate. To facilitate this, the donor country may have to offer support in excess of the training and include equipment and support for infrastructural improvement of the receiving institution. The recipient may similarly be requested to produce a personnel plan which gives a reasonable assurance that the trainee will indeed have a chance to practise the expertise gained. Both of these aspects of personnel management have been largely overlooked in the past, adding to the less than perfect record of development assistance.

On a very Nordic note, more consideration is given to the training in remote sensing of women rather than men. At first this may seem a rather gender-biased approach, but it is my experience that well-trained men tend to be promoted out of their technical field of excellence and into senior administrative or managerial jobs much more rapidly than women. Much as I - with my cultural background - deplore this, I believe that it would be a clever move to employ more women in remote sensing in developing countries, as they appear to constitute a more stable workforce (not withstanding their child-bearing tasks). This is particularly so in digital fields, where men appear to be quickly lured into highly paid jobs, e.g., in the private sector.

Human resources development is a key issue for future development in remote sensing applications in the third world. I am frequently asked to suggest the scientific background that remote sensors should have. If the interpretation of images is strictly visual, I believe no one can beat a scientist familiar with the subject (e.g., a geologist for geology, a soil scientists for soils, etc.). When interpretation is largely based on digital processing, I am no longer so sure because it is very important to be familar with both computer processing and applied statistics. These skills underlie algorithms and logic of digital image processing and no thematic skills can compensate for lack of reasonable aptitude in these two basic fields. On the other hand, no untrained statistician or computer buff can hope to make a reasonable interpretation of a theme. Fortunately, the young modern scientist may have training in both, but it is my sad experience that third world universities often lack computing staff and facilities for adequate digital training and also often neglect some of the hard statistics so necessary for digital image processing.

DATA AVAILABILITY

Remotely sensed data has now reached a stage where it is realistically priced. Gone are the days when you could have Landsat imagery for a few postage stamps. Essentially this is a healthy development in a commercialized world. However, this results in greatly reducing the demand for such data, particularly in the developing world where the need is probably the greatest. Today very few, if any, third world countries buy satellite imagery at commercial and hard currency prices. The activities are very largely based on grants and subsidies provided by the industrialized donor community.

This situation is likely to persist for a long time. Thus the regional centres for remote sensing that are supported by the United Nations, the World Bank and others will essentially depend on the goodwill of the donors in providing the data. It seems reasonable to me that donors accept this situation. Insistence on purchase of data, whether "reasonably priced" or not, will effectively limit the utility of data already recorded.

There has been a marked tendency for increased use of low-priced weather satellite imagery, particularly the National Oceanic Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) data, and largely for vegetative biomass. The pioneering efforts done by C.J. Tucker and his group at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center deserves great praise, regardless of what some colleagues think of algorithms like the Normalized Difference Vegetation Index.

The increasing number of satellite receiving stations located in the developing world reduces the reliance on on-board tape recorders that are notoriously unreliable. The timeliness of data is similarly enhanced. Although some geographical gaps remain, the coverage from receiving stations appears to be approaching a reasonable level. Improved satellite telecommunication links are now able to transport data fast between countries. Provided the donors maintain their support, we can expect such facilities to be increasingly used.

As more modern archiving systems become functional in European, United States and Soviet space agencies, the logistics of providing support will be greatly eased. We have seen significant improvement in the last few years in relation to the Satellite Probatoire pour L'Observation de la Terre (SPOT) and Landsat imagery in particular. This trend is likely to continue and be of help for, for example, early warning systems and selection of imagery over humid areas with frequent cloud cover. It may be unusual in discussing trends to put so much emphasis on organizational, human resources and economic and logistic aspects, but remote sensing is a typical technology-driven activity and so much of the discussion has focussed on wavelengths, classification algorithms, sensor stability and the nitty gritty of engineering and data processing. But the softer issues above are equally important and normally neglected.

TECHNOLOGY TRENDS

Remote sensing spans a wide field, and some branches, for example photogrammetry and thematic air photo interpretation, are firmly established technologically. It is doubtful that their importance will diminish significantly in the near future, neither in developed nor developing countries.

The availability of microwave imagery in the near future will expand the scope of operational remote sensing significantly and allow insight into phenomena of wind and waves as well as in cloud-covered areas. Microwaves from radar satellites also carry important messages on crop stands. For third world countries, the processing of radar data, for example SAR, may prove excessively costly.

It is, therefore, likely that the microwave revolution may well be of the secondary type in the third world, relying on already processed imageries provided by the few well-equipped computer centres in the industrialized countries.

It is uncertain as to whether laser technology in remote sensing will find much use in the near future in developing countries. The technology is still sufficiently experimental that large-scale operational use is still speculative.

As data processing becomes more available also in the third world, the so far very useful visual interpretation of the "photographs" constituted from the digital data will have a real competitor from digital image analysis. Although visual interpretation will always provide useful support, much more will be done digitally by the year 2000.

Apart from the microwave sensor, we may not be seeing very many new types of sensors during the next decade. The launch programmes of the major remote sensing nations are beginning to formalize and there are no obvious great leaps forward.

TRENDS IN APPLICATIONS

So far, many of the applications in the third world are connected to basic resource inventories. I foresee a significant change into surveillance and monitoring of the environment. Increased emphasis on sustainable development, concern for land degradation and the effects of pollution require the types of tools that are just provided by remote sensing. It is rapidly becoming a global concern to use and to preserve the local and the global environment. There is no better tool than remote sensing in support of these efforts. Although the technology may still come from the industrialized countries for the rest of the decade, the ground reference data that turn remote sensing from digital signal processing into a meaningful management tool are in the hands of the developing world. I could wish that third world countries were much more aggressive in their liaison with rich-world scientists, demanding returns for their provision of the reference data. The international literature is becoming crowded by Western scientists telling about their discoveries of third world phenomena, while the subject of scrutiny may not have funds even to subscribe to the journal to read the good news. United Nations initiatives, however, such as this workshop narrow the gap between the remote haves and the remotely sensed have-nots. Provided the donor communities continue the good support they have given in some countries, we may yet see that the best tools we have for monitoring of our fragile environment may still be available to those who need them the most.

PLANNING AND MANAGEMENT OF REMOTE SENSING PROJECTS*

Martin Hedlin
Swedish Space Corporation
Kiruna, Sweden

ABSTRACT

Use of remote sensing techniques is one method among others to collect, analyze, structure and interpret information regarding certain areas or conditions of interest.

The main interest, or the real project, for the user might be to carry out forestry work, soil conservation activities, road construction or a population census. In these and many other projects, properly produced and used remote sensing information products can be a useful and practical method to obtain the required and necessary information basis in order to plan and successfully carry out and complete the desirable actions.

The satellite-based remote sensing techniques, however, are still very new and rapidly developing; possible applications are many and varying and the standardization of products is still quite low.

For many users the acquisition and use of remote sensing information products are more likely than not still an occasional activity. The definition of the appropriate product may need a pilot study, development work and also adaption of the production process, etc. The end-user must be fully engaged in many activities and from the suppliers' organization various competencies and skills must be involved, including those of application oriented salesmen, product development personnel and production staff.

These circumstances indicate that many, at least bigger, customer orders are difficult to handle entirely as an ordinary production routine. Thus, the activities required to produce remote sensing information products can often benefit from being considered and managed as project work. Consequently, the concept of remote sensing projects in this paper refers to the production of appropriate remote sensing information products.

INTRODUCTION

Every organization is normally created and adjusted to carry out some specified recurrent and ordinary business or operations. Work tasks and responsibilities are well defined and communication and control routes are established. Consequently, the flexibility is restricted to handle nonrecurrent assignments demanding contribution and co-ordination of resources and skills of various kinds.

---

* This paper, which was presented at the United Nations Training Course in Remote Sensing Education for Educators, organized in co-operation with the Government of Sweden, Stockholm and Kiruna, Sweden, 14 May to 15 June 1990, does not necessarily reflect the views of the United Nations.

The project work concept has developed in order to meet and satisfy the requirements of such non-recurrent assignments and tasks which contrast with the organization's ordinary and routine work. The project work concept however is far from uniform. It is successfully used in many contexts and activities and also with different meanings. In this section we will outline and comment on some general aspects on project work which also are of relevance to remote sensing projects as hinted in the previous section.

SOME DEFINITIONS

A project is a target-oriented, temporary activity with allocated resources and special working procedures, delimited from but usually highly dependent on the ordinary activities. A project organization is a temporary organization given the responsibility and also the authority and competence of carrying out a specified and decided project.

Project management comprises the planning, controlling and co-ordination of the project resources and activities. Project administration implies the application of the administrative rules, procedures and means necessary for an efficient project management.

Project Management

The project management tasks are in many projects carried out by a steering or decision-making group and on day-to-day basis by the project leader. Some of the most important and crucial tasks are briefly described below.

(a) Objectives

Every successful project must have a well-defined objective or set of objectives. The definition of objectives depends mostly on the type, size and complexity of the project. Objectives are always needed regarding the expected result, such as a product specification, the time-limit and the cost limit. Often objectives cannot be clearly specified until after some work has been done.

Early, vague objectives must then be given a more concrete form in the project and when needed, submitted to the steering group for decisions so they can give necessary guidance to the project work. Thus, objectives should be specified and clarified step by step from an initial overall framework. The end-user or the customer must be fully engaged in the definition of objectives for the project, e.g., product specifications, time and cost, etc. After all he or she is the one who must have the final say about work and products which he or she is buying and paying for.

It is also necessary to make the objectives known and accepted by every project member to direct the work in the desired direction.

(b) Structuring and Planning

Planning aims to reduce uncertainty, to provide direction and control, to form the basis for division of work and responsibility and to facilitate the co-ordination of activities. The project objectives must be carefully analysed in order to specify contents and delimitations for the work to be done.

Structuring means that a suitable approach including a clear division in subprojects, stages, tasks, etc. must be found and established to make the work manageable and to provide control and decision possibilities. Hence, it is normally very useful if every stage and task, etc., can be specified so that a tangible result of each stage and task can be defined to facilitate follow-up.

Further planning is then needed at different levels of detail, such as a project plan outlining the whole project, stage plans for the decided project steps and detailed plans for the next stage or period. The necessary degree of detail depends on many factors, including:

- project size;
- timing and anticipation needed;
- degree of difficulty and complexity;
- knowledge and experience of tasks; and,
- participating project peronnel.

Planning must for each task reach the level of detail where the knowledge, experience and competence needed can be specified, the amount of work estimated and the timing established. Every task or activity must be clearly specified, which includes:

(a) prerequisites for start that are clearly explained and demonstrated;

(b) resource requirements that are calculated;

(c) time needed and available that is fixed; and,

(d) individual responsibility is established.

Only when the realistic resource and competence requirements, cost calculations and time schedules are elaborated and compiled is it possible to establish the necessary foundation for managing the project so as to reach the target.

Planning, however, is a recurrent activity, always combined with and depending on follow-up information, and where the degree of detail is pushed forward stage by stage as the project work advances. Planning is normally the project leader's responsibility; however, it should not normally be his task alone.

Appropriate resource requirements, time schedules and cost calculations must often be based on a wide variety of knowledge and experience. Only then can estimates be well founded and plans, schedules and calculations realistic. Therefore, a broad participation of the project members in the planning process is necessary.

Organization and Staffing

The previous structuring and planning form the basis for the project work and guarantee adaption to the objectives and the contents of the project. A common way of organizing projects is to form a steering or decision-making body and a reference group and to appoint a project leader and a required number of project teams. In doing this, it is essential to try to keep the project organization and staffing limited and manageable.

Once the necessary resources have been identified and specified, the project leader also must secure the personnel needed including requirements for specialists. This must often be done through negotiations with the ordinary line organization. Also other in-house resources, equipment, etc., are usually needed for the project work, hence the strong need of co-ordinating project work with ordinary activities. Normally also external resources must be planned, negotiated, purchased and directed.

It can be necessary to include training in special topics, in methods and aids to be used and also to inform and instruct regarding the project work approach, monitoring and routines.

Organizing and staffing must to some extent be done in parallel with the initial structuring and planning in order to involve project participants in the planning process, benefit from expertise and increase commitment to plans and objectives. As a matter of fact, one of the earliest actions in every project is a staffing decision, to appoint the project leader.

A firm commitment to the project work is needed from every project participant as well as from their superiors. Responsibility and authority should be specified for each team member as well as the task, the expected work-load needed and the result to be produced.

Follow-up and Reporting

In the follow-up stage, it is necessary to find out what really happened and to compare with the original objectives and plans. The follow-up includes time spent, resources used and achievements made. This comprises the input necessary for corrective actions and the recurrent planning activities. Planning must always be combined with a regular follow-up; otherwise, it will lose all importance as a project managing tool. Therefore, follow-up has these aims:

(a) controlling project progress;

(b) provide facts for decision making; and,

(c) spread information regarding the project.

Thus regular follow-up is necessary to know how the work is progressing, to reveal any need of rescheduling and to revise objectives, etc.

The follow-up stage also forms the basis for all reporting to the decision-making group regarding project status and decisions needed, etc. Follow-up information as well as plans and calculations must be systematically gathered and compiled into an organized project documentation which then can also serve a basis for information within the project and to other interested parties. Finally, there is often much to be learned from follow-up and evaluation after the completion and winding-up of the project.

General Problems in Project Work

Project work is problem-solving work. Without careful management and monitoring it easily becomes problem work.

Some phases which are always especially critical are:

(a) project initiation;

(b) transition from pilot work to full-scale implementation; and,

(c) follow-up and completion.

As soon as a project gets started, a series of problems can ensue, including a period of uncertainty, if not confusion, of overall objectives, approaches and organizational matters. A new activity is established partly within the existing organization but with a nonregular task and separate working arrangements. Individuals often will partly continue with their regular tasks and partly participate in the project work. All this can be confusing in the beginning and the atmosphere is too easily repeated in transitions from one stage to the next. The way to deal with such intangibles is through provision of information, training and clear instructions.

If, at the start of a project, there are some problems, it is possible that they will continue in the completion and termination stages. The participants are preparing for their duties and assignments and will gradually slide over especially if the project is delayed compared to originally established plans and agreements. Also, the end-user or customer normally must again be very much involved in the last project stages, which can cause timing problems. One way to deal with this kind of problem is to jointly elaborate very detailed plans and schedules for the final activities, to which everyone adheres.

Other circumstances which easily create problems are:

- incomplete break-down of activities and tasks; and,

- lack of commitment in the organization and among the participants.

The first of these issues concerns planning. Too many projects get out of control resulting in exceeded time-limits and costs due to incomplete breakdown of the work involved. The type and amount of work is not properly estimated and planned and consequently neither are the know-how and resources needed. At the best this will result in delays and cost increases and then also in various co-ordination problems. Thus it is of decisive importance during the planning process to break down activities to a level where full understanding is reached, allowing for appropriate estimates.

The second issue concerns realization. If participating personnel or their superiors lack commitment for the project work, they will easily be absorbed by other competing tasks. Thus, it is also necessary that non-regular but planned and approved project work and tasks taken seriously and be carried out in accordance with agreements made. To improve commitment, senior management should officially support the assignment and participants should be involved in planning and project work as early as possible.

THE ROLE OF THE PROJECT LEADER

The project leader's key responsibility is to about bring results in accordance with decided objectives, calculations and plans. The leader is the key figure in the project, the one upon whom much of the day-to-day progress will depend. However, the project is also supposed to work when the project leader is absent. Thus, it is necessary to appoint a deputy and to see that the deputy has real responsibilities to take over and lead the work forward when the project leader is absent.

The project leader has continuously to perform three roles:

- planning;
- staffing; and,
- co-ordinating.

The project leader will be depending on the expert knowledge and experience of the team members in order to elaborate realistic plans. Such qualifications are, notwithstanding, admittedly important to create a basis for leadership and judgement. Most of the project leader's work will be devoted to personnel and co-ordination matters to keep the project moving ahead. He or she is responsible for acquiring and committing the right personnel at the appropriate time and seeing that the team members are of one mind about the objectives.

Project work, however, is to a large extent teamwork. The project leader's most important role is often to create and maintain a smoothly operating team. One important way to achieve this is to be firm about agreed objectives and plans, commitments and decisions made.

COMBINATION OF FIELD DATA AND REMOTE SENSING DATA*

Hakan Olsson
Swedish Space Corporation
Kiruna, Sweden

INTRODUCTION

In this paper the view on resource inventory methodology given in remote sensing courses and the literature will be supplemented with some concepts developed in the field of forest inventory. The basic sampling principles used in forest inventory can often be modified to other fields of resource inventory, such as fuel wood, crops, soils, etc.

In the remote sensing literature, the performance of different automatic classification procedures is often discussed. The collection of ground truth data for training of the classifiers is often treated as a necessary add-on for the digital procedures, instead of as an integrated whole. It is typical for the literature on ground data collection to emphasize radiometric measurements. This knowledge is only of interest for basic radiometric research. For applied studies, it is enough to measure the properties to be studied, such as forest volume, together with the co-ordinates of the field site. Sources for ground truth in the applied studies mentioned in the literature have been based on old serial photos, various maps and on some field visits.

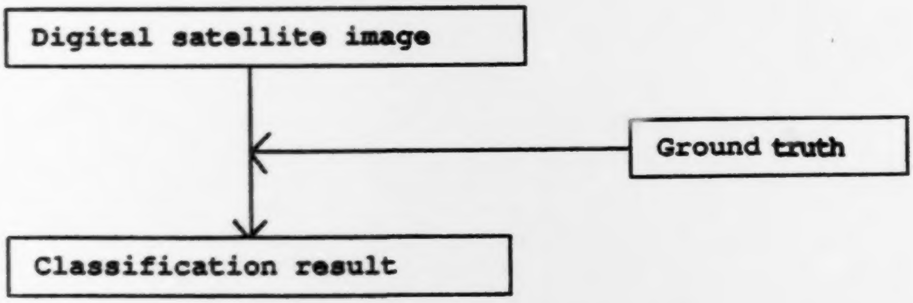


Figure 1. The view of classification for land cover mapping given in the remote sensing literature.

The result of this process is a digital map. The area covered by the different land cover classes can easily be measured. However, an evaluation often shows that the classification accuracy on pixel level is limited. The limitations of the traditional multispectral classification approach have been pointed out.[1] Some of the most important factors causing automatic classification that still remain in the research phase are:

---

* This paper, which was presented at the United Nations Training Course in Remote Sensing Education for Educators, organized in co-operation with the Government of Sweden, Stockholm and Kiruna, Sweden, 14 May to 15 June 1990, does not necessarily reflect the views of the United Nations.

- different land cover classes might have the same spectral signature;
- human interpreters still interpret the context where a site is located better than the computer; and,
- computer classification needs expensive equipment and skilled personnel.

In practically oriented operational projects carried out by the Swedish Space Corporation in recent years, visual interpretation has consequently often been used instead of automatic classification. For example, in the land-use mapping of the Philippines and the fuel wood assessment project in the United Republic of Tanzania, visual interpretation of computer enhanced images was considered to be the most practical approach.

Despite these concerns, it is my firm belief that the remote sensing information can be operationally used in a more automatic way and with more useful results than are often seen today. Important features of satellite data are that they are digitally stored, they can be automatically combined with other data sources if co-ordinates are available and unbiased estimates can be automatically produced.

This paper will concentrate on the possibility of estimating the area distribution for different land cover types. The examples will be taken from the forestry sector, where this section has been studied for long time, most often without the use of remote sensing technology. The directions where fruitful combinations of these two working methods can emerge are indicated in this paper.

The traditional forest inventory approach is illustrated in figure 2.

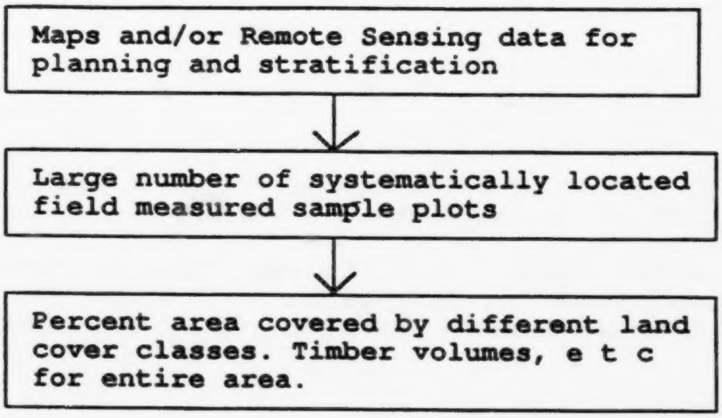

Maps and/or Remote Sensing data for planning and stratification
Large number of systematically located field measured sample plots
Percent area covered by different land cover classes. Timber volumes, e t c for entire area.

Figure 2. Basic principle behind ground-based forest inventories.

GROUND BASED SAMPLING METHODS IN FORESTRY

A comprehensive handbook on forest inventory methods is that of Loesch-Zohrer-Haller.[2/] Forest inventory methods can be divided into subjective and objective methods.

An example of a subjective inventory is the mapping on the scale of 1:10,000 or 1:20,000 for operational forest management planning carried out by forest enterprises in Sweden. The forestry compartments are delineated from serial photos or satellite images. Each compartment is then visited in the field, where basal area, heights, etc., are measured in parts of the compartment selected on site.

In objective inventories, all measurements are made on plots with locations determined by a sampling plan. Typical measurements are tree diameters, that is, species counting and descriptions of the site where the plot is located. The key feature of objective sampling methods is that the rules for data collection may not be modified in the field. The rules should be designed to give an unbiased result. A simple rule of this kind involves sampling of plots in a square grid. The distance between each plot is, for example, 100 m. The starting-point and the orientation of the sampling grid can preferably coincide with the co-ordinate system of the maps used. Figure 3 illustrates a simple layout of a field plot for objective sampling.

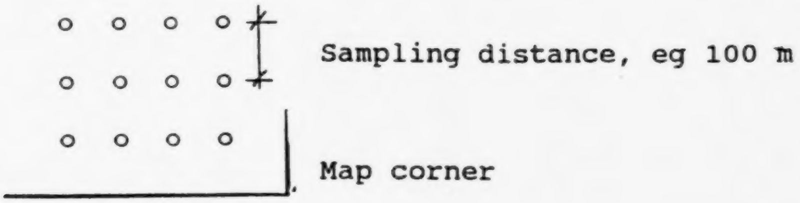


Figure 3. A simple layout of field plot for objective sampling.

Objective methods are used for inventories on a strategic level. A typical example is the National Forest Inventory (NFI) in Sweden. The main purpose of the Swedish NFI is to estimate the growing timber volumes. The inventory should give the information needed for the national forestry policy. Similar inventories are also regularly carried out by the major forestry companies for their internal planning.

In the NFI 20,000 sample plots are laid out in a systematic pattern over Sweden [3/]. Around 10,000 of these plots are located on forest land; all of these will be visited and measured in the field. Forty per cent of the plots are permanent and will be revisited every fifth year; the rest of the lots are new every year.

A plot in the NFI has a radius of 7 m (or 10 m for the per cent plots). The diameter and species are noted for all trees on the plot. Data for large amounts of other variables, in total around 200, are also collected. These data describe various properties of the plot site, such as soil and hydrology. The data are collected and stored in hand-held field computers.

The field plots are located along the sides of square clusters, called "tracts". The distances between each plot within a tract are some hundred metres. The distances between the tracts are several kilometres.

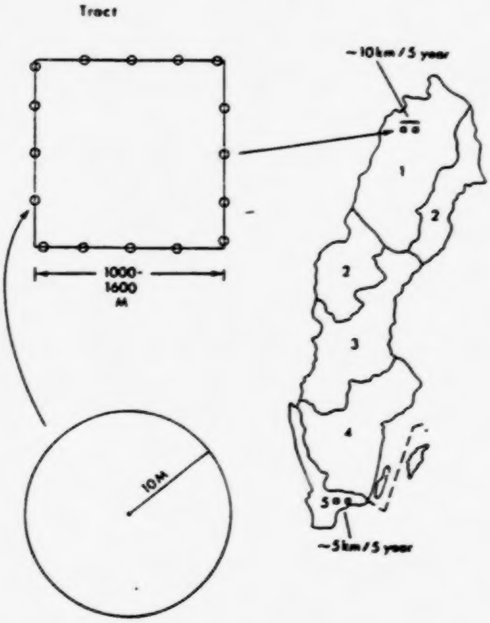


Figure 4. The principle for layout of plots and tracts in the Swedish National Forest Inventory.

Possibilities for including remote sensing in the Swedish NFI in the future are currently being investigated.

STATISTICAL METHODS FOR COMBINING FIELD PLOTS AND IMAGE

In combining field data and satellite data different statistical techniques are applicable. An understanding of the different possibilities requires a good understanding of sampling theory. For those interested in designing resource surveys with the aid of remote sensing data, the study of some textbooks on sampling theory[4] might give the necessary theoretical background. Some of the important techniques are reviewed in short here.

Ratio and Regression Estimators

In a number of sample plots 1..n where, e.g. the timber volume y is measured in the field and we want to estimate the mean volume y for an area, if the grey values in the satellite image are correlated with the timber volumes, the satellite image might aid in telling us how representative our sample is $y_1 .. y_n$.

$\bar{X}$ = mean grey value for all pixels in the forest area.
$\bar{x}$ = mean grey value for the pixels corresponding to the ground sample 1..n.
$\bar{Y}$ = mean volume for the ground sample.

The ratio estimate is:

$$\hat{Y}_{ratio} = \bar{X} * (\bar{y} / \bar{x})$$

And the regression estimate is:

$$\hat{Y}_{reg} = \bar{y} - b\,(\bar{x} - \bar{X})$$

where b is the regression coefficient when y is regressed on x.

DOUBLE SAMPLING REGRESSION

Double sampling is also called two phase sampling. If the large first phase x above also is obtained through sampling, we have an example of double sampling. For satellite data interpretation, this might be the case if the image in the first phase is interpreted as plots in a grid and a portion of these plots in a second phase are visited in the field.

We will thus have the regression estimate:

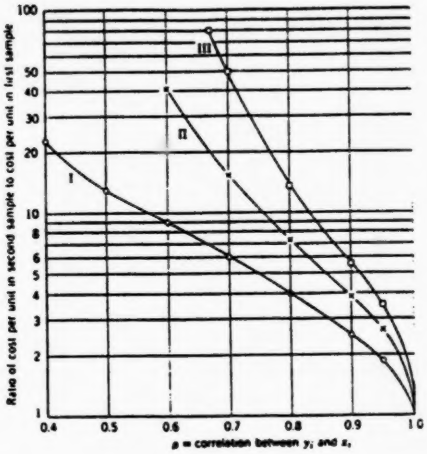
$$\hat{Y}_{reg} + \bar{y} - b\,(\bar{x} - \bar{X})$$

But in this case, X is the mean for a (relatively large) sample of the total population. Given the costs to obtain the auxiliary first-phase sample of x and the final (and more expensive) second phase sample of y and the variance in the two samples, the optimal allocation between the first and the second phase samples can be estimated. Given this optimal allocation, it can be shown that double sampling for regression in theory is cost-effective compared to one-phase random sampling if:

$C_s/C_f > (1 + \sqrt{1-r^2})^2 / r^2$ 5/

where Cf = cost for one unit in first phase sample (= 1 plot in image)
Cs = cost for one unit in secondary phase sample (1 field plot)
r = the correlation coefficient between the x and y

The following diagram indicates correlations and cost ratios during which double sampling for regression might be cost-effective.



I: Double and single sampling equally precise.

II: Double sampling gives 25% increase in precision.

III: Double sampling gives 50% increase in precision.

Figure 5. Relation between Cs/Cf, coefficient of correlation and increase in precision by double sampling for regression.[6]

STRAFIFIED SAMPLING

An alternative way to utilize an auxiliary variable x that are obtainable for all elements in the population is through stratification. The population I..N is divided into 1..h relatively homogeneous strata through the aid of x. The number of samples in each stratum is then selected depending on the variance and cost for sampling in the stratum. Among the advantages with stratified sampling are:

(a) different types of sub-populations might be treated independently in the survey;

(b) if the strata are internally homogeneous, the total variance might be smaller than without stratification, because the variance of the total estimate is the sum of the variances within the strata; and,

(c) instead of reducing the variance, the cost might be minimized.

In accordance with the above, the auxiliary variable x might be obtained as the first-phase sample in a two phase sampling, if it is not already present for the total population.

TWO-STAGE SAMPLING

In two-stage sampling, a sample of primary sampling units (PSU) is first drawn. This might, for example, consist of forest stands in a preliminary forest map. In the second stage, a number of secondary sampling units (SSU) are drawn. The SSU's are elements within the PSU's, such as circular plots within the forest stands. Two stage sampling might be practical (and therefore also more economical) when the sample survey is carried out. For example, it is less costly to visit a limited number of stands for an accurate inventory than to spread out the field check to a large number of plots. However, for a given number of SSU's, two-stage sampling will give larger variance than the corresponding simple random sampling.

EXAMPLES OF REMOTE SENSING PROJECTS AND TECHNIQUES

Techniques for Forest Inventory

The information to be estimated by forest inventories are total volumes, species combinations, etc., for a given area. Maps are not always required.

A straightforward way to use images as part of a sampling design is to interpret sample plots located on the image in a regular grid pattern. The result from the photo-interpretation is the large and relatively inexpensive first phase sample (x). In the second phase a portion of the plots are visited in the field for complete field measurements of the final variables (y). Double sampling for regression using this principle has recently been tested by the Swiss Department for NFI.[7][8] Interpretation of aerial photos used was the first phase. The coefficient of correlation between photo-interpretation and ground plot was around 0.65 and the estimated total reduction of cost compared to field sampling only was around 10 per cent.

Figure 6, from Jaakkola [9], illustrates the principles of both two-stage sampling and two-phase sampling. As PSU was 6*50 pixel blocks in the Landsat scene were chosen. A random sample of the PSUs was selected as SSU's. The timber volume in the SSU's was estimated with sample plots in a two-phase design. In the first phase, all plots were interpreted in 1:15,000 aerial photos. In the second phase, a portion of the plots was visited in the field.

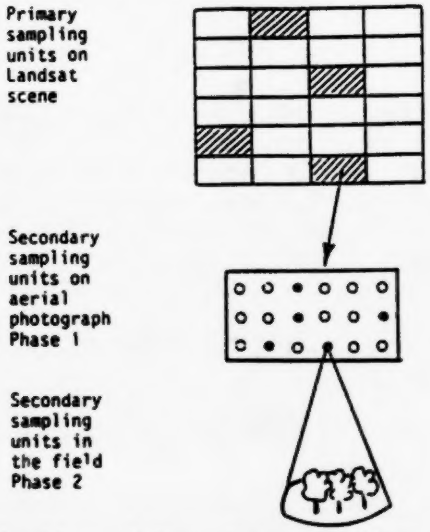

Primary sampling units on Landsat scene
Secondary sampling units on aerial photograph Phase 1
Secondary sampling units in the field Phase 2

Figure 6. A combination of two-stage sampling and two phase sampling.[10]

In Laos, a first reconnaisance survey of the forest resources in the country is currently being carried out. The survey is based on 1:30,000 scale aerial photos from 1981. A systematic sample of stereo pairs, covering the entire country, is selected as a first-phase sample.

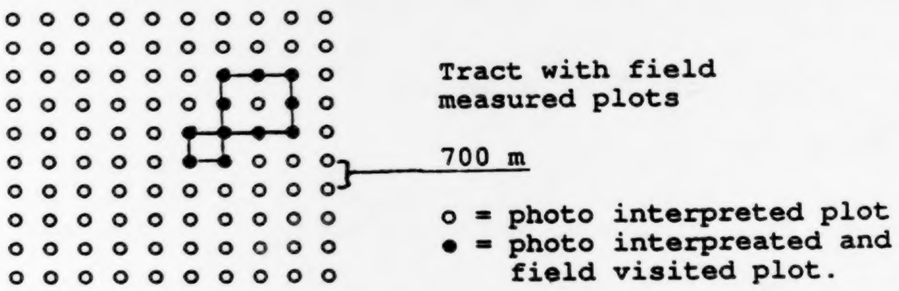

Tract with field measured plots
700 m
o = photo interpreted plot
● = photo interpreated and field visited plot.

Figure 7. Principle for pointwise sampling in Laos.

Over each stereo pair a grid of 10 by 10 sample plots is placed, with 700 m between the plots. The forest type for each plot is interpreted in stereoscope by two independent interpreters. Multispectral SPOT images from 1988 and 1989 are also interpreted for a sub-sample of the plots. On the SPOT images major changes, like burnings in the forest for agriculture, can be interpreted. Thus a matrix of land-use changes can be constructed. In the reconnaissance survey the interpreters have made extensive field visits for their own training. A systematic field inventory with measurements on sample plots is planned in the second phase of the inventory, which is called the National Forest Inventory (NFI). The tracts in the NFI will be linked to a subsample of the photo interpreted plots; thus a double sampling design will be obtained.

TECHNIQUES FOR FOREST MAPPING

A modern method for forest mapping under development is to segment the image into spectrally homogeneous areas and then classify the segments. The first advantage with this approach is that mapping units (compartments) of realistic size are obtained (e.g. around 1 ha). The second advantage is that the estimates of forest parameters become more accurate if they are based on mean values from a number of pixels. Segmentation belongs to the field of advanced image processing. Basically, two different approaches are used:

(1) edge detection which means finding the segments between detected edges in the image;

(2) region growing, which means finding similar pixels from a detected kernel point.

Current research projects in Sweden 12/ and Finland 12/ have used the directed trees algorithm for segmentation.13/ The basic steps in this algorithm are:

(a) if necessary, reduce the noise in the image with low pass filtering, e.g. median filtering;

(b) run an edge detecting filter, such as the sobel filter, to obtain a derivative of the original image, where high values mean large changes in grey value;

(3) run the directed trees algorithm, which assigns pointers to each pixel indicating the neighbour pixel with lowest change value - pixels with no lower neighbours will be kernels, surrounded by a number of associated pixels.

Unfortunately, very few remote sensing packages do have advanced segmentation algorithms commercially available yet. If and when such systems are purchased in the future, an important additional feature would be that the segmentation results, if needed, could be manually changed by a user-friendly editor.

Given the segments of homogeneous areas the volumes, tree species combinations, etc., for each segment might be estimated. Due to the fact that each segment contains several pixels (around 10-100), the estimates of segment level are much more reliable than estimates of stand level. Regression estimators are used to obtain continuous estimates of, e.g., volume, instead of discrete classes.14/ To obtain the regression functions, the field variables and the corresponding grey values from the plots of the Swedish NFI can be used. The results for stand level seem to be comparable with the results for traditional subjective forest inventories. Due to the fact that the NFI is an unbiased sample of all forests, it is possible to use the above, or some other, remote sensing technique, to extrapolate an unbiased estimate for every piece of forest land. Even if accuracy is limited at the pixel level, the error of the mean will decrease considerably when estimates of the mean for larger areas are made. In a geographic information system (GIS) environment, flexible estimates for different geographic areas, such as a county, can be made.

A procedure15/ in which the satellite data are used for stratification has been described. In the first phase, all forestry pixels in the satellite data are classified using, e.g., unsupervised pixelwise classification. This procedure gives a number of strata. For each stratum, a number of "second-phase" field plots are randomly selected. From these field plots the mean volumes, species combinations, etc., or each pixel in a given stratum can be calculated. The results can be aggregated on any geographical unit, e.g., forest stands, defined by segmentation of aerial photo interpretation, or larger administrative units.

THE USE OF SAMPLE PLOTS FOR EVALUATION OF ACCURACY

An independent collection of field measured sample plots might also be used to evaluate the quality of, e.g., a forestry map, produced by interpretation or automatic classification. It is then important for the plots to be systematically or randomly located, and not sampled only among the roads, etc. Given a confusion matrix, different types of accuracy calculations can be made, such as:

- Producers' accuracy = probability that a reference ground sample will be correctly classified;
- Users' accuracy = the probability that a sample from the classified image actually represents that category on the ground;
- Kappa coefficient of conditional agreement, as a measure of individual class accuracy.16/

The kappa coefficient for a given class is defined as:

$$Ki = (N * X_{ii} - X_{i.} * X_{.i}) / (N * X_{i.} - X_{i.} * X_{.i})$$

where:

X_{ii} = number of correctly classified pixels for class i
$x_{.i}$ = number of field plots for a given class
$X_{i.}$ = number of sampled map units for a given class.

NOTES

1/ Ryerson, R. "Image Interpretation Concerns for the 1990's and Lessons from the Past," Photogrammetric Engineering and Remote Sensing, Vol. 55, No 10, (1989).

2/ Loetsch, Zöhrer, Haller. Forest Inventory, vols. 1 and 2, BLV (Verlagsgesellschaft, München, 1973).

3/ Ranneby et al., "Designing a new national forest survey for Sweden", Studia Forestalia Suecia, No. 177, Swedish University of Agricultural Sciences, Uppsala (1987).

4/ Cochran, W. Sampling Techniques, third ed., (John Wiley & Sons, New York, 1977).

5/ Ibid.

6/ Ibid.

7/ Köhl M., "Double Sampling in the Swiss National Forest Inventory: Results of a pilot study", In: Proceedings from the SNS/IUFRO Remote Sensing for Forest Inventory Workshop, 26-28 February 1990, Umea, Sweden.

8/ Sutter, R., "Increasing Efficiency in Volume Estimation by the Combination of Aerial and Terrestial Samples in the Swiss NFI," In: Proceedings from the SNS/IUFRO Remote Sensing for Forest Inventory Workshop, 26-28 February 1990, Umea, Sweden.

9/ Jaakkola, S., "Use of the Landsat MSS for Forest Inventory and Regional Management: the European Experience," Remote Sensing Reviews, vol. 2, (1986), pp 165-213.

10/ Jaakkola, S., "Use of the Landsat MSS for Forest Inventory and Regional Management: the European Experience," Remote Sensing Reviews, vol. 2, (1986), pp. 165-213.

11/ Hagner, O., "Computer aided forest mapping and estimation of stand characteristics using satellite remote sensing," Remote Sensing Laboratory, (Swedish University of Agricultural Sciences, 1989).

12/ Tomppo, E. "Stand delineation and estimation of stand variates by means of satellite images," In: Proceedings from the SNS seminar on remote sensing aided forest inventory, Hyytiala, Finland, 10-12 December 1986.

13/ Narendra, P.M. and Goldberg, M., "Image Segmentation with Directed Trees", IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. PAMI-2, No. 2, (1980), pp. 185-191.

14/ Hagner, O., "Computer-aided forest mapping and estimation of stand characteristics using satellite remote sensing", Remote Sensing Laboratory, (Swedish University of Agricultural Sciences, 1989).

15/ Poso, S. et al. "Forest Inventory by Compartments Using Satellite Imagery," Silva Fennica, vol. 21, No. 1, (1987), pp. 69-94.

16/ Rosenfield, Gerard, Fitzpatric-Lins, K., "A coefficient of agreement as a measure of thematic classification accuracy," Photogrammetrie Engineering and Remote Sensing, vol. 52, (1986), pp. 223-227.

OPERATIONAL USE OF RADAR IMAGES: FROM AIRBORNE TO SPACEBRONE MISSIONS*

J.F. Dallemand
Remote Sensing Centre
Food and Agriculture Organization of the United Nations
Rome, Italy
and
J. Lichtenegger
European Space Research Institute
European Space Agency
Frascati, Italy

INTRODUCTION

Since 1972, the year of the launching of the first Earth Resources Technology Satellite (ERTS), space remote sensing has evolved toward operational applications. Nevertheless, one of the factors limiting the use of remote sensing in agriculture and renewable-resources studies on an operational basis has been the problem of availability of data. Because of atmospheric conditions and cloud cover, a multi-temporal approach to land-use mapping suffers from certain problems. This situation has been partly resolved by the French Satellite Probatoire pour l'Observation de la Terre (SPOT) and its off-nadir viewing capacity that increases the revisit cycle time; the combined use of SPOT and Landsat thematic mapper (TM) high-resolution imagery for the same region is now possible, but in some tropical areas there is still a pronounced lack of information. This is where radar imagery and its potential for thematic mapping can be of special importance to those countries. Also, in addition to the all-weather capacity, another advantage of the use of radar sensors is that they can obtain information on physical parameters, while optical sensors give more information on the material content of the objects.

Until recently, all orbital Synthetic Aperture Radar (SAR) data were produced during short-term missions: SEASAT, 1978; Shuttle Imaging Radar (SIR-A), 1981; and SIR-B, 1984. The European Space Agency Remote Sensing Satellite ERS-1 will be the first long-term mission to include an imaging SAR.

While microwave remote sensing missions are in preparation for the 1990s, ERS-1 of the European Space Agency, RADARSAT from Canada, JERS 1 from Japan and the practical contribution of the 1970s Side-Looking Airborne Radar (SLAR) missions for renewable-resources studies should not be forgotten. The assessment of the information content of these radar images and of the complemantariness of microwave and optical data is a preparation for the use of future orbital SAR images.

---

* This paper, which was presented at the United Nations/Food and Agriculture Organization/European Space Agency Microwave Workshop, organized in co-operation with the Government of Brazil, Sao José dos Campos, Brazil, 19-23 November 1990, does not necessarily reflect the views of the United Nations.

ERS-1 is mainly designed for marine applications, but it will provide SAR images of the land surface, within the limits of programming and within the receiving range of ground stations. A large part of North Africa and Europe will be covered by ESA stations. Stations in Latin America, India and elsewhere in South-East Asia are under consideration.

SLAR (SIDE-LOOKING AIRBORNE RADAR) PRESENTATION

Radar is an active system that emits electromagentic radiation in a wavelength between 6 mm and 1 m. The antenna of the radar system sends a narrow beam of energy to a distant object; part of this energy is backscatterd by the target toward the radar. In the case of SLAR, the intensity of the radar pulse backscattered by the land is registered photographically, and the film is either analyzed in real time or stored for later analysis.

Among the factors that affect the SLAR image are:

(1) Wavelength

For example, the capacity to penetrate a dry soil is related to wavelength and will be higher in L band (25 cm) than in K band (2.75 cm).

(2) Plane stability (attitude)

Now SLAR systems include devices for compensation of attitude variations so that we have no modification of the geometry and contrast.

(3) Depression angle

The depression angle 0 is the angle between the horizontal and the line from the antenna to the terrain. A low-depression angle gives the best information on slight terrain undulations; it will enhance topography and will be adapted, for example, to forestry studies. On the other hand, a high depression angle will be more suitable for mountainous areas because it will reduce shadowing effect.

There are two distinct categories of imaging radar systems:

- Real-aperture systems (called brute-force radars);
- Synthetic aperture radars (SAR).

Real-aperture radars generally operate in the K and X bands. With these systems, spatial resolution is a function of antenna size and range (distance from the antenna to the target); therefore, it is not possible to use real-aperture systems at orbital level without abandoning a satisfactory spatial resolution. This is why at orbital level, synthetic-aperture radar

(SAR) is used; it simulates a very long antenna using the motion of the platform and allows a high spatial resolution independent of satellite height:

- 40 metres for SIR-A at 260 km altitude;
- 25 metres for Seasat at 800 km altitude.

EXAMPLES OF SLAR PROJECTS AT OPERATIONAL LEVEL

Brazil

The RadamBrazil project 1/ is the largest mapping programme so far executed using an airborne system (1970-1976). Initially designed to cover only the Amazonian region, it was extended to the entire country (8.5 million km^2). The Radam project was executed using a Goodyear X-band SAR. The aircraft was flown at 11,000 and 12,000 metres, with north-south flight lines and westward imaging. Depression angles were between 13° and 45°, with 20 per cent overlap between image swaths. Optically correlated images of 1:440,000 scale were mosaicked into 1:250,000 scale sheets. After thematic interpretation, 25 reports of "inventory of natural resources" were produced, as well as maps revealing geology, soils, vegetation, and geomorphology at a 1:250,000 scale of the entire territory.

Nigeria

The whole of Nigeria (950,000 km^2) was imaged in 1976 and in 1977 using Motorola X-band real-aperture dual-look radar, under a joint Food and Agricultural Organization (FAO)/United Nations Development Programme (UNDP)/Nigerian Federal Department of Forestry programme. 2/ Scale mosaics at 1:250,000 were produced and interpreted in combination with aerial photography and ground-checking. Sixty-eight sheet maps of land use/natural vegetation were produced.

The real-aperture system was chosen because of:

- Its lower cost compared with airborne SAR;
- The increased information content of dual-look imagery and the lower mission costs owing to the reduced number of flight lines; and,
- Its depression-angle-control capacity.

Colombia

An area of 320,000 km^2 of Colombia was imaged within the Proradam project (Proyecto Radargrammetrico del Amazonas), with an X-band radar, from 1973 to 1979. 3/ Depression angles were between 15° and 39°, with a 52 per cent overlap between strips. Sixty-nine semi-controlled mosaics at 1:200,000 scale were produced, and thematic analysis based on physiographic elements allowed differentiation of:

- Swamp

- Savannah
- Areas affected by human influences

Swamp could be further subdivided by tone into:

- Open water with floating vegetation
- Homogeneous palm
- Palm mixed with low forest
- Low swamp forest.

Interpretation accuracy was checked through a forest inventory. It provided information that could not be extracted on SLAR images, such as present species and volume. The inventory was performed at 874 sampling points (1 ha. each) in 30 pilot areas, and 174 samples were selected along the rivers. The sampling density was 0.0036 per cent.

The image-quality and geometry assessment have been described by F. Leberl. [4] Image-quality assessment was performed on paper prints at 1:400,000 scale by three persons in seven days (1,700 km flight time/day/man). Geometry quality was assessed by triangulation using 500 control points. A quality problem was noted because of high speckle (electronic noise) in near-range data.

Indonesia

SLAR data were used in Indonesia within the Regional Physical Planning Programme for Transmigration (RePPProt), aiming at land planning of a very scattered territory. [5] Thematic maps at 1:250,000 scale were produced after interpretation of radar images and 1:100,000 scale aerial photographs (15 per cent of the territory covered). Land-systems identification was found very acceptable on radar mosaics.

SLAR missions also took place in Gabon, Malaysia, Panama, Peru, the Philippines and Venezuela. Flights are still being executed.

CONCLUSIONS

Airborne radar imagery has already proved to be an efficient tool for renewable-resources studies in developing countries, especially in tropical areas where the use of aerial photography is very limited because of high cloud cover. After the experimental missions of Seasat, SIR-A and SIR-B, there now exists a database of radar imagery from space and more data will be available after the SIR-C mission planned for 1992.

In Europe, the SAR 580, Agrisar and Agriscatt campaigns have already provided interesting results that will lead to a wider use of radar imagery in agriculture. Radar imagery also opens new perspectives for developing countries, where there is still a serious lack of information relevant to cartography, land-use mapping, agricultural statistics, and agricultural and forestry resources. There, the use of radar images in combination with data from other sources, including the National Oceanic Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR), the United States Landsat, the French Satellite Probatoire pour l'Observation de la Terre (SPOT), aerial photo appears to be the best means of achieving good results.

Two pilot studies based on combined analysis of optical and microwave data for agricultural land-use mapping are presently being executed in Tunisia by the FAO Remote Sensing Centre in collaboration with the European Space Agency and the Ministry of Agriculture of Tunisia. Thematic analysis is performed after:

- Image-to-image registration of Seasat, SIR A, Landsat MSS, Landsat TM and SPOT data of the semi-arid area of Msaken in central Tunisia by the Food and Agricultural Organization of the United Nations;

- Digital terrain-model production and geocoding of Seasat, Landsat MSS, Landsat TM and SPOT data for the Mediterranean peninsula of Cap Bon.

In the next few years, more imagery will become available, especially after the launch in 1991 of the ERS 1 satellite of the European Space Agency. This remote sensing satellite will include an active microwave instrument (AMI). The AMI will operate in wind mode to gather information on wind speed and direction at the surface of the oceans, in wave mode to estimate directional wave spectra and in imaging mode (SAR mode). In the latter case, it will provide high-resolution imagery 100 km wide along the track.

NOTES

1/ Radam. Technical Reports. (Brasilia, 1978).

2/ Allen, P.E.T. "The use of side-looking airborne radar (SLAR) imagery for the production of a land-use and vegetation study of Nigeria," United Nations/Food and Agriculture Organization of the United Nations Training Seminar on Remote Sensing of Earth Resources, Ibadan, (1979).

3/ Sicco Smit, G. "Will the road to the green hell be paved with SLAR? A case study of tropical rain forest type in mapping in Colombia," ITC Journal, (1975), p. 2.

4/ Leberl, F. "Evaluation of SLAR image quality and geometry in PRORADAM," ITC Journal, (1974), p. 4.

5/ Laksono and King, R.B. "Application of radar imagery in transmigration planning", Proc. Reg. Symp. on Remote Sensing Applications for Socio-Economic Aspects of the Environment. United Nations Development Programme (UNDP)-Economic and Social Commission for Asia and the Pacific (ESCAP) Remote Sensing Programme, Jakarta, 1985.

MICROWAVE APPLICATIONS FOR WEATHER, CLIMATE AND HYDROLOGY*

Edwin T. Engman
Hydrological Sciences Branch
Laboratory for Hydrospheric Processes
NASA/Goddard Space Flight Center
Greenbelt, MD United States

ABSTRACT

The application of microwave remote sensing to weather, climate and hydrology offers great potential for making measurements that are not possible with other remote sensing instruments. The actual application depends on the relationship betwen the microwave frequency and the interaction or transmission through the atmosphere. This report describes the frequency-atmosphere interdependency and how a remote sensing scientist can optimize the information abstraction through instrument choice. The report then describes the current state of knowledge with specific applications to deriving rainfall, snow, soil moisture and other meteorological and hydrological variables. Finally, the existence of current microwave sensors, archived data sets and future programmes is discussed.

INTRODUCTION

Microwave remote sensing for applications to weather, climate and hydrology offers unique capabilities not found with sensors in the other parts of the electromagnetic spectrum. First of all, microwaves offer all-weather sensing capability. Being able to "see through the clouds" is an obvious advantage for any earth science applications. This is especially so because some parts of the globe have cloud cover much of the time and many of the interesting events in weather and hydrology involve clouds.

The other area in which microwave remote sensing offers unique capabilities for weather, climate and hydrological studies is based on the capability to directly measure the state of the system. Measurements of water vapour content, snow water equivalent and soil moisture are examples of atmospheric and hyrologic state variables that potentially can be measured by microwave sensing. This is in contrast to other regions of the spectrum (except for thermal sensing) where the geophysical variable must be inferred and not measured directly.

---

* This paper, which was presented at the United Nations/Food and Agriculture Organization/European Space Agency Workshop on Microwave Remote Sensing Technology, organized in co-operation with the Government of Brazil, Sao José dos Campos, Brazil, 19-23 November 1990, does not necessarily reflect the views of the United Nations.

This paper discusses the basis for microwave remote sensing in weather, climate and hydrology and then discusses the current state of the science with specific examples. Future applications and potentials are also discussed.

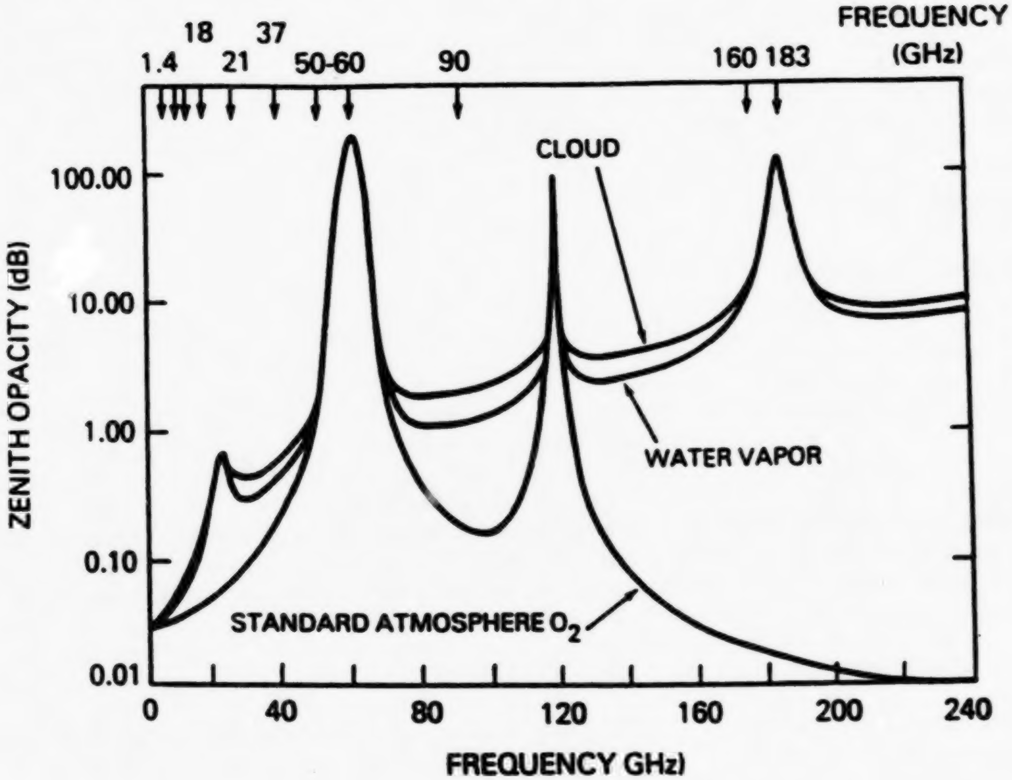
BASIS FOR MICROWAVE REMOTE SENSING

The basis of microwave remote sensing is portrayed by figure 1. Three curves are shown in figure 1: (1) the total zenith opacity for a dry standard atmosphere; (2) zenith opacity for the same atmosphere with 2 g/cm^2 water vapour added to the atmospheric column; and (3) the same column with an additional 20 mg/cm^2 of liquid water added to represent a typical stratus cloud. The dominant features on the figure are resonant lines of oxygen between 50 to 70 GHz (which merge into a band at sea-level pressures) and at 119 GHz (isolated line) and resonant lines of water vapour at 22 GHz and (a very strong line) at 183 GHz. However, except at the resonant lines the atmosphere is relatively transparent in this portion of the spectrum, and as the figure illustrates, the presence of a non-raining cloud is only a small effect.

Remote sensing in the microwave portion of the spectrum is traditionally done at frequencies near 1.4, 6, 10, 18, 21, 37, 55 and 90 GHz, and sensors using 157 and 183 GHz are planned. These frequencies have been indicated for reference at the top of figure 1. They have been intentionally chosen among the peaks and valleys of the atmospheric attenuation curve. Measurements near the resonant peaks are used primarily for monitoring atmospheric temperature or water vapour. For example, measurements using a single frequency near the 22 GHz resonance of the water molecule have been used successfully to estimate the total water in a column of the atmosphere 1/ and are made as part of remote sensing of other parameters from space to help correct for the effects of atmospheric attenuation. The oxygen resonance lines between 50 and 70 GHz are used to obtain profiles of the temperature of the atmosphere, 2/ 3/ and the water resonance at 183 GHz is suited for obtaining profiles of atmospheric water vapour 4/ and sounders to do so are being developed.

Frequencies in the valleys of the attenuation curve are least affected by the atmosphere and are ideally suited for monitoring of the Earth's surface even in the presence of clouds. Measurements have been made of parameters such as sea surface temperature, snow cover, concentration of sea ice and soil moisture. For example, sea surface temperatures have been measured at 18 and 37 GHz, snow cover at 37 GHz and soil moisture at 6 and 1.4 GHz.

At the long-wavelength end of the microwave spectrum, the radiation emitted or reflected from matter is generally determined by the bulk dielectric properties of matter and by such properties as the grain size in snow, the size of inclusions in ice and the shape and size of leaves on trees and other vegetation. Furthermore, microwave radiation at this end of the spectrum penetrates materials such as snow, ice, soil and vegetation. Consequently, it can be used to monitor average bulk properties of such material and is not limited to surface features or absorption and emission at molecular resonances. Consequently, at this end of the spectrum microwave radiation responds differently to the physical properties of matter than infrared or optical radiation and offers additional information to complement



. Microwave absorption in the atmosphere. Lower curve - atmospheric opacity due to oxygen. Middle curve - opacity with 20 kg m^{-2} water vapor added to the oxygen. Upper curve opacity with 0.2 kg m^{-2} stratus cloud added to the oxygen and water vapor.

Figure 1

remote sensing at the very short wavelengths.

Finally, at frequencies in the 10 to 50 GHz range, radiation in the microwave portion of the spectrum penetrates clouds but is strongly absorbed by rain. This provides the potential for measuring rain from space. 5/ 6/ Frequencies near 18 GHz have shown promise for measuring a wide range of rain rates; 7/ however, by combining this observation with measurements at a more attenuating frequency (one near 37 GHz is generally used), one can improve the dynamic range of the measurement by increasing the detectability of the lower rain rates. Some of the more important parameters which can be measured in the microwave portion of the spectrum, together with the frequencies at which these measurements are made, are listed in table 1.

ATMOSPHERIC REMOTE SENSING

Temperature and Water Vapour

Temperature variation with height is a characteristic feature of the Earth's atmosphere. It is common to describe the atmosphere in terms of this temperature variation. For example, the lowest of these layers, the troposphere, averages from 6 to 18 km in depth, depending upon latitude and weather conditions. It is deepest over the equator and shallowest over the poles. It contains approximately 80 per cent of the total gaseous mass of the atmosphere and virutally all the water vapour and aerosols. It is also the zone where weather phenomena and atmospheric turbulence are most marked. This layer is characterized by a general decrease of temperature with height at a mean rate of about 6.5 K/km, and the whole zone is capped in most places by a temperature inversion level and in others by a zone which is isothermal with height. The troposphere thus remains to a large extent self-contained, because the inversion acts as a "lid" which effectively limits convection.

The ongoing studies of the troposphere are focused on the development of an improved understanding of the physical processes important in determining the circulation of the atmosphere on all scales, ranging from the mesoscale to the global scale, and an improved capability to predict its evolution of a wide variety of temporal and spatial scales. The current tropospheric knowledge base for global and regional understanding and prediction has evolved over the last half-century, accelerating in accuracy and scope over the past decade or so. The enhanced prediction accuracy, which has been attained in recent years, can be explained primarily as the result of improved three-dimensional temperature input (from satellites) and wind information (satellite cloud-tracked and aircraft-measured), as well as improved numerical weather prediction (NWP) models. The range of useful prediction by models has increased from four to seven or eight days, and four-day forecasts are now roughly of the same accuracy as two-day forecasts were 20 years ago.

The measurement of atmospheric temperature and humidity, along with wind and sea level pressure, represent the core measurements required to define the dynamic and thermal states of the troposphere. To determine the global atmospheric structure for large-scale dynamical systems and for weather forecasting, observations of temperature and humidity are needed in three

Table 1. Parameters Which are Measured with Microwave Sensors and the Frequencies at Which the Measurements are Made

Physical Observable	Frequency of Observation (GHz)									
	1.4	6	10	18	21	37	50.60	90	160	183
Soil moisture	●	○								
Snow		○	○	●		●		◒		
Precipitation										
Ocean			◒	●	○	◒				
Land				◒		●		●		◒
Sea surface temperature		●	◒	◒	◒	○				
Sea ice										
Extent				●		●		○		
Type		○	◒	●		●		◒		
Wind speed (sea surface)			●	◒	○	○				
Water vapour Total (over ocean)				●	●	◒				
Profile					◒	○	◒	○	◒	●
Cloud water (over ocean)					◒	●		◒		
Temperature profile					○	○	●	○		

● Necessary ◒ Important ○ Helpful

dimensions and at frequent intervals. Optimal measurement systems are likely to make use of both microwave and infrared radiometers. The NWP models can be expected to asymptomatically approach horizontal and vertical resolutions of nearly 100 km and 1 km, respectively, in the quest for improving the accuracy of medium range (1-to 14-day) forecasts.

Clouds play a major role in the radiation balance of the Earth atmosphere system. Definitive climate studies will not be possible until cloud properties are more realistically incorporated in numerical global circulation models. Clouds are also important in many ways for mesoscale weather systems. The evolution of convective clouds and their interaction with their environment is one of the central problems of mesoscale meteorology. A second major problem is precipitation and the processes that determine its spatial and temporal distribution. Even thin layers of non-precipitating clouds affect many mesoscale phenomena through their effect on the surface energy budget. Cloud liquid water content is an important cloud parameter that can be effectively measured by microwave radiometric methods.

ESTIMATING PRECIPITATION

Radiometry

Much work has been done with infra-red data collected by polar orbital and geosynchronous satellites. However, visible and infrared data provide only an indirect estimate of rain rate, microwave observations are directly related to the hydrometers, and therefore represent a great potential for improving satellite precipitation determination. The physics of passive microwave rain measurements fall into two regimes: absorption and scattering. In the absorption regime, one observes rainfall through the enhanced emission associated with liquid raindrops against a cold background. The technique is only applicable over the highly reflective surface of the ocean. This rather direct physical relationship between the rainfall rate and observed microwave radiances can actually be derived from basic physical principles. A relationship between the microwave radiances and the rainfall information over the oceans has been reported. 8/ Also, the Nimbus-5 ESMR data to produce a global rain atlas have been used. 9/

In the scattering regime, on the other hand, rainfall is observed through enhanced microwave scattering within the rain column. This process provides a rainfall signal over any background surface. Since the scattering is primarily due to frozen hydrometers, the relationship to rainfall rate is less direct than in the absorption regime and must be established empirically or through the use of cloud models. The utility of the scattering signal in identifying rain areas using SSM/I data has been described. 10/ A cloud model based algorithm to retrieve rainfall rates from SSM/I 86 and 37 GHz data has been reported. 11/

Microwave radiometry provides a measurement of the instantaneous rainfall rate, whereas the quantity desired for climatological purposes is an integrated rainfall over a certain time period. Therefore, it is necessary for any remote rainfall measurement scheme to deal with the sampling problem and associated uncertainties. This can be approached statistically with a properly designed measurement strategy. Several investigators have developed procedures for obtaining precipitation amounts over land and ocean from sensing multichannel microwave radiometer (SMMR) instruments. Utilizing the newly collected SSM/I data, a preliminary monthly rainfall index over oceans retrieved by a statistical method was reported.[12] Over land several algorithms are now being developed. A preliminary algorithm to retrieve precipitation over land and ocean using the scattering signal was reported.[13] The indirect nature of this approach and the need to estimate the effect of environmental conditions require careful testing before finalizing the scattering-based algorithms.

Ground-based radar

The basis for radar measurement of rainfall is the same whether from ground-based radar or from space. Radar measurement of rainfall is based on the Rayleight scattering caused by the interaction of rain and the radar signal. Assuming the rainfall uniformly fills the radar pulse volume, the power of the radar pulse returned to the antenna can be expressed as:

$$Pr = C_1 C_2 K \Sigma D^6/r^2 \qquad (1)$$

where Pr is the average power returned from the precipitation at distance r, the radar range, C_1 is an instrument parameter, C_2 is related to the dielectric constant of the precipitation (approximately a constant), K is an attenuation factor and D is the raindrop diameter. The radar response to rainfall is wavelength dependent according to D^6/A, where A is the wavelength. Because the radar interacts primarily with the rain, it can identify the presence of rain below the clouds and theoretically, at least, provide an opportunity to measure rainfall rates without several restrictive assumptions.

Ground-based radar is conceptually similar to spaceborne radar except that the radar is stationary and its area of measurement is limited to a circle with a radius up to about 100 km.[14] Figure 2 illustrates the operation of a ground-based radar for measuring precipitation. A recording rain gauge is desirable for calibration. Thus, the rain rate, R, can be estimated according to

$$Z = aR^b \qquad (2)$$

where Z is the measured radar reflectivity and a and b are calibration parameters.

With ground-based radar there are two basic approaches[15] used quantitatively to estimate precipitation:

(a) Single-parameter measurement: this uses either the backscattered radiation which is related to precipitation intensity or the attenuation rate which is related to the precipitation rate;

(b) Multi-parameter measurment: here multi-wavelength radar backscatter is related to the precipitation rate with the dual-polarization capabilities

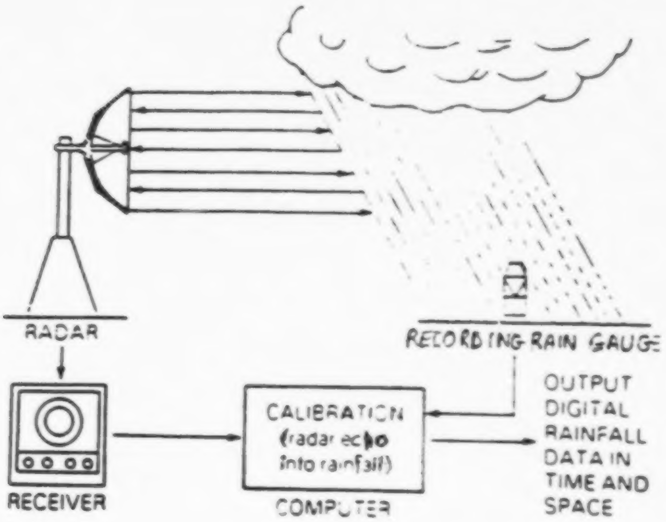


Figure 2. Schematic ground-based radar rainfall measurement

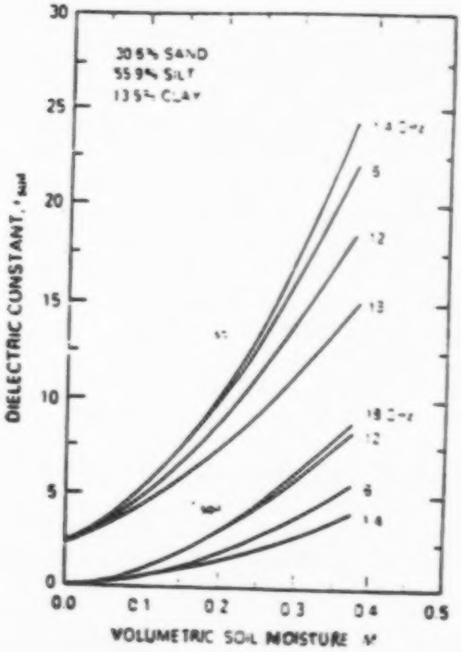


Figure 3. An illustration of the real and imaginary parts of the dielectric constant as a function of volumetric moisture content for a loamy soil measured at four frequencies

being used to give information on the drop size distribution (DSD).

Spaceborne radar

Spaceborne radar differs from conventional radar primarily by the power and antenna size restrictions. The reflectivity to rainfall (Z-R) relations generally require non-attenuating wavelengths (longer than 5 cm), although at shorter wavelengths and lighter rain rates Z-R methods are also applicable. Because the longer wavelengths currently require prohibitively large antenna dimensions to achieve adequate resolution from space, the proposed Tropical Rainfall Measurement Mission (TRMM) radar will utilize a short wavelength of about 2.16 cm (i.e., 24 GHz).

Another advantage of the shorter wavelength is that the attenuation is almost perfectly linear with rain rate and is essentially independent of DSD. Most of the algorithms are based upon the measurement of attenuation, A, and its relation to rain rate, R. When R becomes small, however, the attenuation also becomes small relative to the measurement errors; then we shall resort to the use of reflectivity, and the appropriate Z-R relationship, as our only alternative.

In general, attenuation by rain is given by:

$$A = \int_{0}^{H} kRdH \qquad (3)$$

where A is the total path attenuation in dB, R is rain rate in mm/hr, K is the attenuation coefficient in db/dm per mm/hr, and dH is the incremental path length. In most of what follows we assume that k is independent of R so that we may write $A - kRH$ where R is now the path-averaged rain rate, and H is the total path through rain. In order to deduce R, we therefore need to measure or estimate H. For most purposes this can be taken as the slant range to the height of the freezing level, which corresponds to the top of the bright band in straitform precipitation. This height is also generally known from independent meteorological observations. In convective storms, however, supercooled rain and clouds may occur above the freezing level and then the determination of H is subject to possible errors. One approach to the rainfall measuring question is the surface reference method.[16/] If measurements of the surface return power are made in the presence and absence of rain, the ratio of the powers will be proportional to the path attenuation as long as the surface scattering properties do not change significantly between the two measurements. Advantages of the method are its simplicity and the fact that it estimates a quantity, attenuation, that is highly correlated with rain rate. A possible disadvantage of this method is the uncertainty of the surface scattering in the presence of precipitation. As with most attenuation methods, the accuracy of the surface reference technique is limited at light rain rates where the uncertainties in the measurement are comparable to the quantity to be estimated. For a TRMM-type radar at nadir and a 5 km deep storm over the ocean, the dynamic range is expected to be up to about 90 mm/hr at 14 GHz.[17/] The high rain rate limit is due to the signal being attenuated so strongly that the surface is no longer detectable.

The use of spaceborne radar for measuring rainfall is in its infancy. Much of the current research is directed to algorithm development that is based on single or multiple frequencies or uses combinations of visible band (VIS), infra-red (IR) and microwave sensors.

HYDROLOGIC APPLICATIONS

Soil Moisture

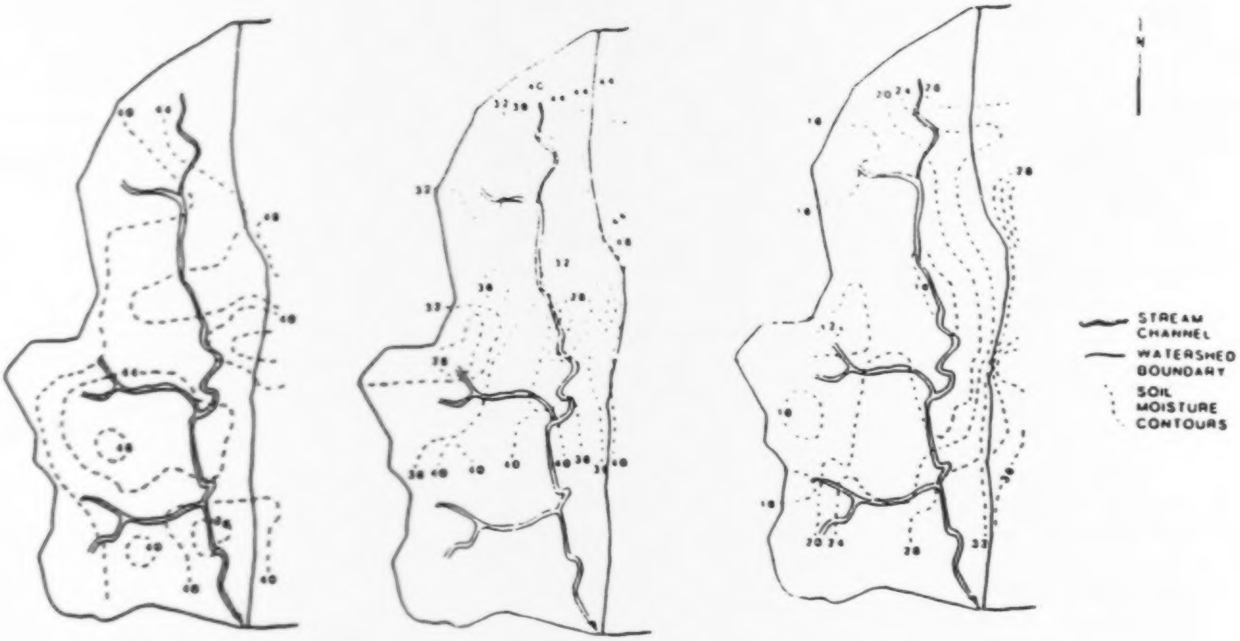
Soil moisture can be defined as the temporary storage of precipitation within a shallow layer of the Earth that is generally limited to the zone of aeration. However insignificant this layer of soil moisture may seem when compared to the total amount of water on the global scale, it is this thin layer that controls the success of our agriculture and regulates the distribution of precipitation between storm run-off and storage. Despite this apparent role of soil moisture in agriculture and water resources, it is a variable that is little used in prediction and monitoring of production and resources. The primary reason for this is its difficulty in measurement.

Soil moisture is highly variable both spatially and temporally, as the result of the inhomogeneity of soil properties, topography, land cover, and the nonuniformity of rainfall and evapotranspiration. Soil moisture is also difficult to measure in a way that is representative of anything except a point. Typically, averages of point measurements are used to characterize the soil moisture of an area, but these averages seldom yield information that is representative of other hydrologic processes (i.e, run-off, groundwater recharge, etc.).

Microwave Techniques

Microwave techniques for measuring soil moisture include both the passive and active microwave approaches, with each having distinct advantages. The theoretical basis for measureing soil moisture by microwave techniques is based on the large contrast between the dielectric properties of liquid water and of dry soil. The large dielectric constant for water is the result of the water molecule's alignment of the electric dipole in response to an applied electromagnetic field. At L-band frequency the dielectric constant of water is approximately 80 compared to that of dry soils, which is on the order of 3 to 5. Thus, as the soil moisture increases, the dielectric constant can increase to a value of 20, or greater. 18/ Figure 3 illustrates the change in dielectric constant for soil at several microwave frequencies. Thus, for passive microwave remote sensing, this change in dielectric constant would result in a decrease of emissivity from about 0.95 to 0.6 or lower. For the active case, the measured radar backscatter would increase by about 10 dB, or possibly by even more.

For passive microwave remote sensing of soil moisture, a radiometer measures the intensity of emission from the soil surface. This emission is proportional to the product of the surface temperature and the surface emissivity which is commonly referred to as the microwave brightness temperature (T_B) and can be expressed as follows:



WATERSHED 1D
MAY 28, 1987

WATERSHED 1D
MAY 30, 1987

WATERSHED 1D
JUNE 4, 1987

Figure 4. Soil moisture map developed from PBMR data for three dates: May 28, May 30 and June 4

$$T_B = eT_{soil} \qquad (4)$$

where e is the emissivity which is dependent upon soil texture, surface roughness, and any vegetation present. Actual soil moisture is usually related to T_B empirically with ground data.

For the active microwave approach, the measured radar backscatter, S_t, is made up of backscatter from vegetation, S_v, and soil, S_s, and the attenuation caused by the vegetation canopy, L. These terms can be related by the following simple model:

$$S_t = S_v + S_s/L \qquad (5)$$

The soil backscatter, S_s, can be related directly to soil moisture by:

$$S_s = R\,\alpha\, M_v \qquad (6)$$

where R is a surface roughness term, a is a soil moisture sensitivity term, and M_v is the volumetric soil moisture. Although R and a are known to vary with wavelength, polarization, and incidence angle, there is no satisfactory theoretical model suitable for estimating these terms independently. Thus, as is the case for the passive microwave approach, the relationship between measured backscatter and soil moisture requires an empirical relationship with ground data, even for bare soils.

An additional approach for using soil moisture data derived with microwave approaches is through change detection. This approach can be used for passive or active microwave data. The change detection method minimizes the impact of target variables such as soil texture, roughness, and vegetation because these tend to change slowly, if at all, with time. With change detection it is assumed that the only target change occurring is the soil moisture. Thus, any measured changes in T_B or S_t can be related directly to changes in soil moisture. Fortunately, both the brightness temperature and backscatter relationships with soil moisture are approximately linear. Also, fortunately for many hydrologic applications, the changes in soil moisture may be more important than the actual absolute value of soil moisture.

As discussed above, microwave techniques for measuring soil moisture have a strong theoretical basis. In addition, they are not limited to cloud free and bare soil conditions because the microwave approach can sense through cloud cover and, in many cases, through a vegetation canopy. However, there are a number of target and target-sensor characterictics that affect the measurement of soil moisture. These include the effects of soil texture, the depth of measurement, surface roughness, vegetation effects, and instrument parameters such as incidence angle and frequency.

Although not yet a truly operational technology, remote sensing of soil moisture has been shown to be possible through a number of research projects. A great deal has been learned from these studies but additional work is needed to define the optimal sensor configurations. Unfortunately, there is no existing microwave satellite system that is collecting data suitable for soil moisture measurement. However, there have been a number of aircraft and a few spaceborne instruments that have demonstrated the feasibility of measuring soil moisture by remote sensing. A few of these studies that have hydrologic implications are summarized below.

The L-band radiometer on the Skylab provided data that were indirectly related to a hydrologic parameter, in this case an antecedent precipitation index. Because the Skylab radiometer was non-scanning with a 110 km field of view, its resulting spatial resolution was very coarse. This resolution prohibited the use of ground measurements to analyze the data. However, by using a more regional indication of soil moisture, the antecedent pecipitation index (API) produced a reasonable correlation between the radiometer data and the API was produced. [19] Satellite radiometer data (18 GHz) have also been used with a vegetation index to model the surface soil moisture for a large part of the south-western United States.

Some early Synthetic Aperture Radar (SAR) results of soil moisture detection were presented when a SEASAT SAR image of an area near Waterloo, Iowa was compared with raingauge data. [20] The radar showed a clear relationship between the bright-return area in the eastern portion of the image, and the rain gauge catch amounts resulting from a rain squall the previous day.

Using data from a series of low elevation aircraft flights with an L-band pushbroom radiometer, it was demonstrated that observed and microwave measured soil moisture patterns were similar to temporal patterns developed with a soil-water simulation model. [21]

Airborne radiometers have been used in the Union of Soviet Socialist Republics for a number of hydrologic applications. Passive microwave radiometers to estimate the presence of shallow groundwater have been used. [22] The problem of identifying areas of seepage from canals was shown to be possible with microwave measurements. [23] The results of flight paths across rivers and flood plains with 30- and 5-cm wavelength radiometers were revealed. [24] [25] Their results demonstrated the potential capability of microwave remote sensing for identifying potentially active hydrologic zones (i.e., partial area hydrology) and for delineating flood plains. As expected, the 30 cm wavelength was more responsive to deeper soil moisture than the 5-cm wavelengths.

In a recent aircraft experiment in Kansas the four beam pushbroom microwave radiometer (L-band) was used to map the spatial distribution of soil moisture. [26] By using overlapping flight lines for several flights during a drying period, the spatial and temporal patterns of soil moisture within a small 37.7 ha watershed were mapped. Brightness temperature maps were developed for the study area. These maps reflect a general drying trend that followed a heavy (6.17 cm) rain on 27 May. In addition to the microwave maps of soil moisture, the small watershed was instrumented to measure the water balance components: precipitation, ET, and streamflow. The microwave data were converted to volumetric soil moisture [27] and plotted as contours of equal soil moisture over the 37.7-ha watershed (figure 4). These patterns illustrate the drying that we expected and also give some hints of the hydrologic processes involved, which were downslope drainage to form channel base flow.

In an attempt to relate the soil moisture to these hydrologic processes, the hydrology for this time period was modelled using a simple sloping slab model. [28] [29] A comparison of the simulated and measured soil moisture is shown in figure 5. These results illustrate that the model and measured data

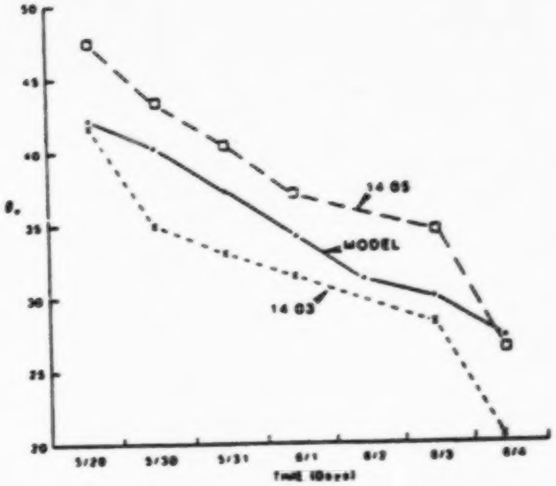


Figure 5. Comparison of model simulated soil moisture and measured soil moisture at two locations on transect 14 (southernmost transect).

agree quite well and that a simple hydrologic model can represent the drying process in a watershed.

Although much additional work needs to be done, this example has demonstrated how a time series of spatial soil moisture data may be used to represent and understand hydrologic processes.

Evapotranspiration

Evapotranspiration is the combined loss of water through the process of evaporation and transpiration. Evaporation occurs from water surfaces and bare soil while transpiration occurs from the canopy cover.

The crucial role of evapotranspiration at regional or global hydrologic scales has only recently been understood. Climatic simulations with global models now demonstrate that precipitation is sensitive to regional evapotranspiration magnitudes. Moreover, evapotranspiration rates vary interannually because of differing air mass characteristics and are subject to human modification through vegetation change.

Also, the rate of evaporation from soil depends on the soil moisture content, as has been described. 30/ During the first stage, when the surface is wet, the rate is limited only by the availability of energy at the surface. As the surface dries, the rate decreases and is controlled by the transfer of water to the surface. The length of time between energy-limited and moisture-limited evaporation depends on the surface soil moisture and the energy available to the surface. Therefore, the rate of evaporation from the soil depends on the soil moisture content.

Transpiration from a canopy depends on the soil moisture available in the volume of soil occupied by active roots, the type of canopy and the energy input to the system. Transpiration itself is not directly measurable by remote sensing. However, transpiration may be estimated using conventional techniques such as the combination equation 31/ or by energy balance techniques which use remotely sensed data as input.

Of these varibles, soil moisture 0 and surface temperature T_s are directly measurable by remote sensing using 1.4 GHz microwave and the 3.5 to 4.0 um, 8 to 9 um, or 10 to 12 um thermal infrared data. Visible and near infrared reflectance measurements may be used to estimate vegetation type and photosynthesis rate, from which the stomatal resistance r_s can be estimated.

There are still some undetermined values. Incoming solar radiation R_s can be estimated from Geostationary Operation Environment Satellite (GOES) data by statistical methods 32/ or can be measured at surface field stations. Wind speed u, aerodynamic resistance r_a and humidity e_a are also needed at the surface. They can be estimated, for example; r_a can be roughly estimated from land cover classification and climatological or approximate values for u and e_a can be used to set bounds.

It is also possible to estimate the evaporation using a mass balance approach by estimating the lower boundary flux from the topsoil layer and agree quite well and that a simple hydrologic model can represent the drying process in a watershed.

Although much additional work needs to be done, this example has demonstrated how a time series of spatial soil moisture data may be used to represent and understand hydrologic processes.

Evapotranspiration

Evapotranspiration is the combined loss of water through the process of evaporation and transpiration. Evaporation occurs from water surfaces and bare soil while transpiration occurs from the canopy cover.

The crucial role of evapotranspiration at regional or global hydrologic scales has only recently been understood. Climatic simulations with global models now demonstrate that precipitation is sensitive to regional evapotranspiration magnitudes. Moreover, evapotranspiration rates vary interannually because of differing air mass characteristics and are subject to human modification through vegetation change.

Also, the rate of evaporation from soil depends on the soil moisture content, as has been described. 30/ During the first stage, when the surface is wet, the rate is limited only by the availability of energy at the surface. As the surface dries, the rate decreases and is controlled by the transfer of water to the surface. The length of time between energy-limited and moisture-limited evaporation depends on the surface soil moisture and the energy available to the surface. Therefore, the rate of evaporation from the soil depends on the soil moisture content.

Transpiration from a canopy depends on the soil moisture available in the volume of soil occupied by active roots, the type of canopy and the energy input to the system. Transpiration itself is not directly measurable by remote sensing. However, transpiration may be estimated using conventional techniques such as the combination equation 31/ or by energy balance techniques which use remotely sensed data as input.

Of these varibles, soil moisture 0 and surface temperature T_s are directly measurable by remote sensing using 1.4 GHz microwave and the 3.5 to 4.0 um, 8 to 9 um, or 10 to 12 um thermal infrared data. Visible and near infrared reflectance measurements may be used to estimate vegetation type and photosynthesis rate, from which the stomatal resistance r_s can be estimated.

There are still some undetermined values. Incoming solar radiation R_s can be estimated from Geostationary Operation Environment Satellite (GOES) data by statistical methods 32/ or can be measured at surface field stations. Wind speed u, aerodynamic resistance r_a and humidity e_a are also needed at the surface. They can be estimated, for example; r_a can be roughly estimated from land cover classification and climatological or approximate values for u and e_a can be used to set bounds.

It is also possible to estimate the evaporation using a mass balance approach by estimating the lower boundary flux from the topsoil layer and snowpack which signals the onset of melt. The microwave potential for snow is based on the sensitivity to the presence of even minute quantities of liquid water in the snow, which results in drastically different dielectric constants of the snowpack. The emission and reflection of microwave radiation exhibit the ability to penetrate not only clouds and most precipitation, but also the snowpack itself, at least under certain conditions. However, microwave interaction with snow is extremely complex because snow properties such as depth, dryness, crystal size, liquid water content and the underlying soil all affect the response. Active microwave systems offer extremely good spatial resolution from space platforms at the expense of greater complexity in the analysis and interpretation of the data. On the other hand, passive systems may result in simpler data intepretation at the expense of relatively poor spatial resolution.

Microwave measurements from satellites could help to remedy both problems, as well as provide information on snow wetness. Albedo and surface temperatures can be obtained with measurements in the visible and infrared and probably will be adequate even if knowledge is restricted to clear conditions.

The capability of microwave remote sensing of snow properties has been summarized. 36/ Snow cover extent is the easiest parameter to measure from orbit. Microwave data allow snow cover extent to be monitored through clouds. Because dry snow has such low emissivity at microwave frequencies, snow boundaries can usually be delineated at 18 GHz or 37 GHz. However, the microwave signature of melting snow may resemble that of bare ground, and concurrent measurements of snow extent from satellite visible data may be helpful to resolve the boundary in such cases. Alternatively, the snow boundary can be observed at night after the snow has refrozen.

In addition to the snow cover area, remote sensing techniques can provide additional information about the snowpack. Snow depth can in some cases be inferred from visible data if the snow depth is less than about 30 cm. 37/ Differences in albedo determined from the National Oceanic and Atmospheric Administration (NOAA) satellite with snow depth in the south-eastern United States have been correlated. 38/ However, this approach is limited to relatively shallow snowpacks.

Recent passive microwave research based on theoetical concepts 39/ 40/ has led to simple snow depth algorithms. A snow density of 0.30 and a grain size of 0.35 to develop the following algorithm was assumed: 41/

$$SD = 1.59\ [T_B(18H) - T_B(37H)] \qquad (7)$$

where SD is the snow depth in centimetres and $T_B(18H)$ and $T_B(37H)$ are the brightness temperatures for the SMMR 18 and 37 GHz polarization channels respectively.

Measurement of snow water equivalence from microwave emission is in its infancy, but development of a successful method would be a significant achievement in hydrology. For snow of a given grain size, microwave emission decreases as the water equivalence increases, but an increase in grain size also causes emission to decrease. Moreover, the influence of grain shape and snowpack stratigraphy are unknown. When snow is wet, emission increases substantially, as does the optical depth of the snowpack. For dry snow, however, a method can probably be developed using a multifrequency, dual-polarized sensor. The higher frequencies (18 and 37 GHz) would be useful for shallower snow, while 5 to 10 GHz would be useful for deeper snow. Multiple frequencies are necessary to cover the range of snow water equivalences expected. Increases in microwave emission with the presence of liquid water in the snowpack are especially noticeable at 18 and 37 GHz.

Many of the microwave measurements of snow properties have been conducted with truck and aircraft experiments. The results from a field data collection programme in which both active and passive microwave truck-mounted instruments were tested were reported.[42/] Both the scattering coefficient and the emissivity were found to be sensitive to changes in snow water content and liquid water in the snow. Figure 6 shows the relationships for water equivalent and figure 7 illustrates the diurnal response of both the active and passive systems to the formation of liquid water in the snow through melting, and its subsequent refreezing.

Ice

The surface of the Earth at high latitudes is unique because it is generally covered with an extensive blanket of snow and ice. This highly reflective covering prevents the heat of the Sun from warming the glaciated land and insulates the ocean by inhibiting the loss of thermal radiation to the atmosphere. Because of this property of the ice and snow blanket for moderating the energy exchange at the surface, changes in this cover can have an important effect on climate.

The natural cycle of ice ages is now further complicated by man's activities. Burning of fossil fuels and deforestation of the land are contributing to a steady increase in atmospheric CO_2. Given that CO_2 can trap heat within the atmosphere, a global warming has been predicted that could seriously alter the present extent and configuration of the polar ice cover. Because the high surface albedo at the poles reduces the amount of radiative energy penetrating the surface, a climatic change causing a reduction in the ice cover can lead in turn to further warming as solar radiation heats the previusly ice-covered land and ocean surfaces. Indeed, climate models indicate that such a warming will be significantly amplified in the polar regions. Eventually, sufficient warming can affect even the great ice sheets, causing them to shrink with an accompanying rise in sea level. Therefore, a fundamental question confronting polar research programmes is to determine whether the world's ice masses are growing or shrinking.

Microwave observations have the potential for greatly refining our estimates of the surface balance. The microwave emissivity of a snow surface is sensitive to the grain size and its distribution with depth, which is determined mainly by snow accumulation rates and snow temperature. Preliminary ice-sheet accumulation maps have been derived based on an empirical relationship between observed emissivity and the few measured accumulation rates. In regions where extensive accumulation rate measurements have been made, significant variations in surface balance were observed over distances on the order of kilometres.

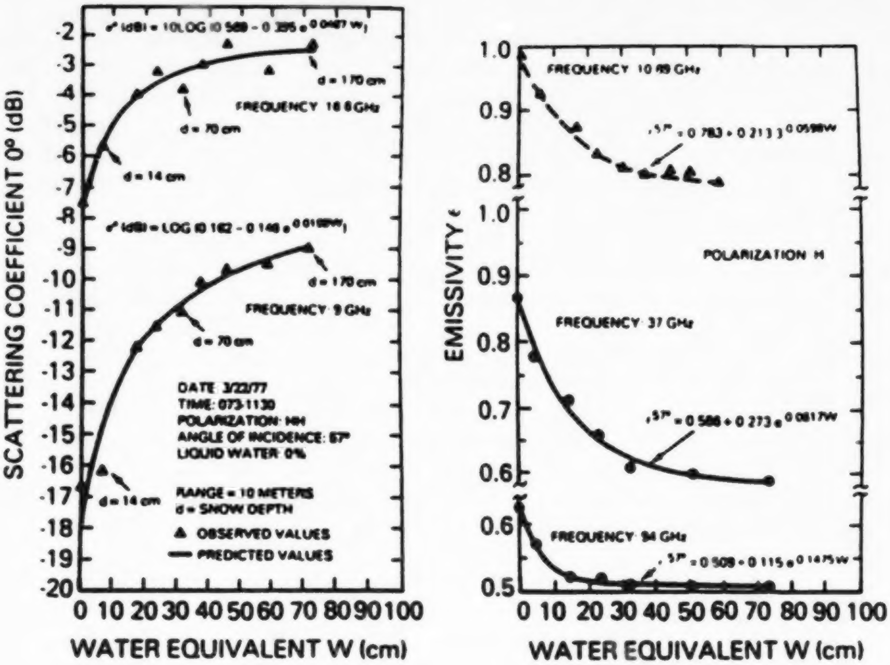


Figure 6. An illustration of the scattering coefficient response to snow water equivalent (left)and the brightness temperature response to snow water equivalent (after Stiles et al., 1981).

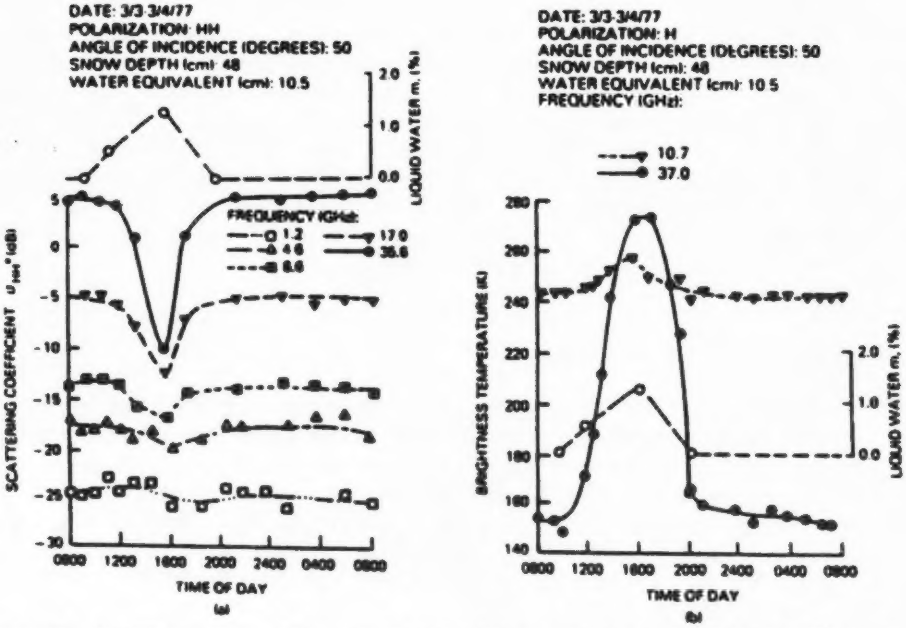


Figure 7. An illustration of the sensitivity of the scattering coefficient (left) and brightness temperature (right) to the presence of liquid water in the snowpack (after Stiles et al., 1981).

Two measurements are crucial to an understanding of the role of sea ice in the climate system. The first is the extent and concentration of the polar sea ice cover and the second is the distribution of sea ice thickness. The importance of the variation of ice thickness across the Arctic to both the dynamics and thermodynamics of the region has been noted in recent studies. 43/ 44/ This is especially true of energy exchanges at the surface during winter.

Multichannel microwave instruments have the potential not only of measuring ice concentration and thickness, but also of allowing the determination of such additional variables as ice temperature, snow cover and surface melting. The SMMR on the Nimbus-7 satellite has 10 channels of microwave information, and algorithms to extract various sea ice parmeters from the SMMR data have been developed and tested by groups in Norway, Canada and the United States. 45/ 46/ 47/ A major restriction of the Nimbus-7 SMMR data for studies of the Central Arctic has been that the satellite's orbit prevents data collection poleward of 84°, in contrast to the global data collection of the Nimbus-5 ESMR.

For sea ice, the parameters which need to be measured are location of the sea-ice boundary, concentration of ice, ice type, albedo and the state of surface melting. The spatial requirements for these measurments exhibit a dual threshold. One set of useful observations is achieved at a spatial seal of 25 km, which corresponds to the diurnal change in the gross extent of the ice boundary. The enhanced capabilities, which require resolutions of 1 to 10 km, represent the scale needed to monitor convergence and divergence processes that affect ice mass balance, hence the total production determines the heat exchange into the atmosphere.

Eventually, a complement of visible, infrared, and microwave sensors will be needed to provide all the information required in the cryosphere; however, microwave sensors have proven to be the most useful instruments to date for collecting information from space over the Earth's poles. The reasons for this success are: (1) microwave instruments are little affected by the clouds and fog which frequently shroud the polar regions; (2) they are unaffected by the polar night which inhibits the use of optical instruments; and (3) the large difference between the microwave emissivity of water and ice makes discrimination between them relatively easy.

FUTURE MICROWAVE REMOTE SENSING

The previous sections have discussed the basis of microwave remote sensing and presented some examples of how these data have been applied to weather climate and hydrology. As promising as these few examples are, the future for the operational use of microwave data is somewhat uncertain. For the next few years, researchers will be limited by the lack of suitable data. Only intensive and science-driven aircraft experiments will be available for collecting soil moisture data in a form that agriculturalists and hydrologists will find useful. Fortunately, there are a few experiments planned in the next few years, and these should be invaluable for providing sample data for developing and testing application models as well as anwsering some of the target-sensor quetions.

Looking ahead to when there may be microwave sensors on orbiting platforms, one confronts the basic differences between passive and active instruments and the intended use of the data. Comparing the instruments simplistically, the active sensors have the capability to provide high spatial resolution data (on the order to 10's of meters) but their sensitivity to soil moisture may be confused more by roughness, topographic features and vegetation than the passive systems. On the other hand, the passive systems, although less sensitive to target features, can provide spatial resolutions only on the order of kilometres to tens of kilometres from a space platform.

One must then consider how the data will be used. Meteorological and climate models currently use computational cells on the order of 10 to 100 km, which may be well within the capability of future passive systems. However, if one is interested in more detailed hydrologic process studies and partial area hydrology, the passive data would appear to be of little use. It is in this context that the active systems appear promising. For example, the Shuttle Imaging Radar (SIR-C/X), a Synthetic Aperture Radar (SAR), to be flown in 1993 is capable of at least 20 m resolution over a swath width of 15-30 km. SAR also has the capability of a scanning mode (SCANSAR) to cover a much wider swath (300-500 km) at a reduced resolution (250 m). At this stage, SCANSAR is a theoretical option; it has not been demonstrated, nor has its sensitivity to useful soil moisture values been demonstrated. Future space launch manifests include several SARs but no passive systems that have frequencies low enough to be useful for soil moisture. It should be noted that currently the shuttle missions will be rather short, a week to 10 days.

Several new satellites are planned for launch over the next decade which will carry payloads and make measurements relevant to the land part of the hydrologic cycle. There are several satellites, such as the European Space Agency's Earth Remote Sensing ERS-1 satellite , or the Japanese JERS-1, which have primarily oceanographic applications but which will also be used for acquiring data over land. The Canadian RADARSAT will focus on ice and sea ice questions as well as land sensing. All will carry single-polarization single-wavelength synthetic aperture radars, plus radiometers at various wavelengths which may also give useful data over land. The duty cycles and coverage of the SARs will be limited in some cases, but the use of SAR data for mapping, particularly in polar areas where overlapping satellite ground tracks mean that the repeat inteval between data on different days is reduced, is clearly of interest to the hydrology community.

The Tropical Rainfall Measurement Mission (TRMM) and Earth Observation Satellite (EOS) of the United States are two of the planned systems that will be of great interest to hydrologists. The Tropical Rainfall Measure Mission, to be launched into an orbit inclined at about 30°, will have on board a rainfall radar that will be capable of estimating rainfall rates over land. The orbit is such that any point within the Tropics will be sampled twice each month at every hour.

EOS and its counterpart European and Japanese platforms will lead to considerable advances in the understanding of the whole earth sciences,

Table 2. Research satellites in the planning phase, but not yet under construction

Tropical Rainfall Measurement Mission (NASA Japan)
Objective: estimate tropical rainfall
Orbit: ± 30°, 320 km, rapid precession
Launch date: January 1994
Payload
AVHRR: vis. and 10 m IR, 1 km resolution, 600 km swath
Microwave radiometer: 19, 37, 90 GHz dual polarised, 10 km resolution, 600 km swath
Radar: 14 and 24 GHz [illegible] 250 m range resolution [illegible]

NASA Polar Platforms NPOP 1 and NPOP 2
Objective: Earth observations for global change
Orbit: polar, 705 km, sun-synchronous
Launch dates: January 1997, 1999, 2002, 2004, 2007, 2009

Payload chosen from:

Instruments	*Mass* (kg)	*Power* (W)
Optical surface imaging		
MODIS-N	278	425
MODIS-T	159	203
MISR	113	54
HIRIS	897	175
ITIR	422	578
CERES	125	104
EOSP	35	15
Tropospheric sounding		
AIRS	170	405
AMSU	154	125
HIMSS	412	59
Radars		
ALT	306	251
SCANSCAT	704	729
STIKSCAT	330	378
Tropospheric composition		
MOPITT TRACER	102	192
TES	675	602
Upper-atmosphere sounding		
HIRRLS DLS	221	286
SAGE III	81	17
SAFIRE	422	410
MLS	620	274
SWIRLS	156	265
Particles and fields		
IPEI	59	8
XIE	121	47
SEM	40	38
GGS	90	104
ENACEOS	42	21
POEMS	181	149
Others		
LIS	16	20
SOLSTICE	262	10
GLRS	603	668
GGI	130	117
WBDCS	48	14
COM PKG	83	25
Total	8034	7666

European Polar Platform-1 (EPOP 1)
Objective: earth science research
Orbit: sun-synchronous, 824 km, 10:00 a.m. equator crossing
Launch date: January 1997
Payload

Instruments	*Description*
AMRIR	A NOAA operational instrument on the ESA platform; a follow-on to the AVHRR and HIRS may also include characteristics of the low light level channel flown on the DMSP
AMSU-A	Microwave radiometer instrument
AMSU-B	Microwave radiometer
DB	Direct broadcast communications
ARGOS	Provides platform location and sensor data from fixed and mobile platforms anywhere in the world
CERES	Two broadband scanning radiometers, one in a cross-track mode and one with rotating scan plane; three channels on each scanner will be a total channel (0.2 to > 100 μm), SW channel (0.2–3.5 μm) and an LW channel (6–25 μm); nadir field of view about 25 km
SARSAT	International cooperative search and rescue system
SCATT-2	An active microwave system intended to measure surface wind speeds (vector) over the oceans in the range from 4 to 20 m s⁻¹
MERIS	Imaging spectrometer designed to operate in very narrow bands in the vis.–near-IR band of the spectrum with a resolution tuned to ocean/meteorology/climate applications
SAR-C	C band SAR
MIMR	A dual-polarization passive imaging microwave radiometer intended to provide information on surface characteristics
ATLID	Four cross-track scanning backscatter lidar
LISA	Infrared interferometer for the investigation of stratospheric composition

European Polar Platform-2 (EPOP 2)
Objectives: earth science research
Orbit: sun-synchronous, 705 km, 10:00 a.m. equator crossing
Launch date: July 2000

Instruments	*Description*
SAR-C	C band SAR
HRIS	High-resolution imaging spectrometer
HRTIR	Push broom radiometer
MERIS	Imaging spectrometer designed to operate in very narrow bands in the vis.–near-IR part of the spectrum with a resolution tuned to ocean/meteorology/climate applications
ALT-2	An adaptive pulse limited radar altimeter designed to operate over land and ice as well as ocean; a dual-frequency radar altimeter including a passive microwave radiometer mode for tropospheric correction
LISA	Infrared interferometer for the investigation of stratospheric composition

Japanese Polar Platform (JPOP-1)
Objectives: earth science research
Orbit: sun-synchronous, 800 km
Launch date: September 1998

Instruments	*Description*
LAWS	Lidar atmosphere wind sounder—tropospheric winds
AMSR	Advanced microwave scanning radiometer to measure water vapour, precipitation rate, and snow and ice extent
AVNIR	Advanced visible and near-IR radiometer
OCTS	Ocean colour and temperature sensor
SAR-L	L-band synthetic aperture radar
SAR-X	X-band synthetic aperture radar

including hydrology. Although the draft manifest of instruments shown in table 2 is impressive, the organization of the data and of other earth science data in an information system where time series of all the data will be easily available is of at least equal importance. The data system will also allow many types of data to be used simultaneously to calibrate or be assimilated into numerical models.

NOTES

1/ Staelin, D.H., "Passive microwave techniques for geophysical sensing of the Earth from Satellites", IEEE Trans. Antennas Propag., AP-29, (1981) p. 683.

2/ Ibid.

3/ Njoku, E.G., "Passive microwave remote sensing of the Earth from space-A review", in Proceedings of the IEEE, vol. 70, (1982) p. 728,

4/ Ibid.

5/ Atlas, D., C.W. Ulbrich and R. Meneghini, "The multiparameter remote measurement of rainfall", Radio Sci., vol. 19 (1984) p. 3.

6/ Wilheit, T.T., et al., "A satellite technique for quantitatively mapping rainfall water over oceans", J. Appl. Meteor., vol. 16(s) (1977), p. 551.

7/ Atlas. op. cit.

8/ Wilheit, T.T., op. cit.

9/ Rao, M.S.V., W.V. Abott, III, and J.S. Theon, "Satellite derived global oceanic rainfall atlas (1973 and 1974)", NASA X-911-76-116, GSFC, Greenbelt, MD (1976).

10/ Spencer, R.W., H.M. Goodman and R.E. Hood, "Precipitation retrieval over land and ocean with the SSM/I Identification and characteristics of the scattering signal", J. Atmos. and Oceanic Tech., vol. 6, (1989), pp. 254-273.

11/ Adler, R.F., et al. "Cloud model-based simulations of satellite microwave data and their application to an SSM/I rain algorithm", Proceedings of the Fourth Conference on Satellite Meteorology and Oceanography, San Diego, CA, 16-19 May 1989.

12/ Chang, A.T.C., and T.T. Wilheit, Rainfall index over oceans derived from SSM/I data, Proceedings of IGARSS'88 Symposium, Edinburgh, Scotland, 13-16 September, (1988d) pp. 251-252.

13/ Adler, op. cit.

14/ Schultz, G.A., "Remote sensing of watershed characteristics and rainfall input", In: Unsaturated Flow in Hydrologic Modeling-Theory and Practice, NATO ASI Ser., Ser.C, vol. 275 (ed. H.J. Morel-Seytoux), (Kluwer, Dordrecht, 1989) pp. 301-323.

15/ Dahlstrom B. "Estimation of precipitation by remote sensing techniques", in Remote Sensing Applications to Hydrology and Water Resources, Proc. Int. Semin. organized by the Slovak Hydrometeorological Institute and Datasystem K.U.O., UNESCO Technical Documents in Hydrology (1985) pp 46-56.

16/ Meneghini, R., et al., "Comparisons of methods using data from an airborne dual wavelength radar", Preprint vol., 23rd Conf. on Radar Meteor. and the Conf. on Cloud Physics, (Amer. Meteor. Soc., Snowmass, CO, 1986) pp. 100-103.

17/ Okamoto, D., and T. Kozu, "Conceptual design of TRMM radar" (unpublished report). Radio Res. Lab. (Japan), 3 April 1987.

18/ Schmugge, T.J., "Remote sensing of soil moisture: Recent advances", IEEE Trans. on Geosci. and Remote Sens., vol. GE-21, No. 3 (1983), pp. 336-344.

19/ McFarland, M.J., "The correlation of SKYLAB L-band brightness temperatures with antecedent precipitation", in Conference Hydrometeorology, preprints, Fort Worth, Texas (1976), pp. 60-65.

20/ Ulaby, F.T., B. Brisco and M.C. Dobson, "Improved spatial mapping of rainfall events with spaceborne SAR imagery", IEEE Trans. on Geosci. and Remote Sens. Let., vol. GE-21 No. 1 (1983) pp. 118-121.

21/ Jackson, T.J., P. O'Neill, "Temporal observations of surface soil moisture using a passive microwave sensor", Remote Sens. Environ., vol. 21 (1987), pp. 281-296.

22/ Basharnov, et al., "Remote sensing of subsurface soil moisture by means of microwave radiometers", Water Resour. Res., Vol. 5 No. 4 (1979) pp. 538-542.

23/ Shutko, A.M., "Microwave radiometry of lands under natural and artificial moistening", paper presented at Symposium on Signature Problems in Microwave Remote Sensing, Union Radio Sci. International, University of Kansas, Lawrence, Kansas (1981).

24/ Armand N.W., A.E. Basharnov, and A.M. Shutko, "Recent microwave radiation studies of continental covers", Acta Astronaut., vol. 6 (1979), pp. 647-655.

25/ Basharnov, op. cit.

26/ Wang, J.R., et al., "Mapping soil moisture with L-band radiometric measurements", Remote Sens. Environ., vol. 27 (1989), pp. 305-312.

27/ Ibid.

28/ Sloan, P.G. and I.D. Moore, "Modeling subsurface storm flow on steeply sloping forested watersheds", Water Resour. Res., vol. 20, No. 12 (1984), pp. 1815-1822.

29/ Engman, E.T., G. Angus and W.P, Kustas, "Relationships between the hydrologic balance of a small watershed and remotely sensed soil moisture", Proc. IAHS Third International Assembly, Baltimore, IAHS Publ. No. 186 (1989) pp. 75-84.

30/ van Bavel, C.H.M., and D. Hillel, "Calculation potential of actual evaporation from a bare soil surface", Agricul. meteor., vol. 17 (1976) p. 453.

31/ Monteith, J.L., "Evaporation and the environment", Symp. Soc. Exp. Biol., vol. 19 (1965), p. 205.

32/ Tarpley, J.D. "Estimating incident solar radiation at the surface from geostationary satellite data," J. Appl. Meteor., vol. 18 (1979), p. 1172.

33/ Arya, L.M., J.C. Richter, and J.F. Paris, "Estimating profile water storage from surface zone soil moisture measurements under bare field conditions," Water Resour. Res., vol. 19 (1983), p. 403.

34/ Prevot, L.R. Bernard, D. Taconet, and D. Vadal-Madjar, "Evaporation from bare soil evaluation using a soil water transfer model and remotely sensed surface soil moisture data", Water Resour. Res., vol. 20 (1984), p. 311.

35/ Colbeck, S.C., "A simulation of the enrichment of atmospheric pollutants in snow cover run-off", Water Resour. Res., vol. 17 (1981), p. 1383.

36/ Foster J.L., D.K. Hall, A.T.C. Chang, and A. Rango, "An overview of passive microwave snow reseach and results", Rev. Geophys. Space Phys., vol. 22 (1984), p. 195.

37/ McGinnis, D.G., J.A. Pritchard, and D.R. Wiesnet, "Determination of snow depth and snow extent from NOAA-2 satellite very high resolution radiometer data", Water Resour. Res., vol. 11 (1975), pp. 892-902.

38/ Ibid.

39/ Hallikainen, M., "Retrieval of snow water equivalent from NIMBUS-7 SMMR data: Effect of land cover categories and weather conditions", IEEE J. Ocean Eng. vol. OE-9 (1984) pp. 372-376

40/ Chang, A.T.C. Chang, J. Foster and D.K. Hall, "NIMBUS-7 derived global snow cover parameters", Ann. Glaciol., vol. 9 (1987), pp. 39-44.

41/ Ibid.

42/ Stiles, W.H., F.T. Ulaby, and A. Rango, "Microwave measurements of snowpack properties", Nord. Hydrol., vol. 12 (1981), pp. 143-166.

43/ Hibler, W.D., "Modeling a variable thickness sea ice cover", *Mon. Wea. Rev.*, vol. 108 (1980), p. 1943.

44/ Maykut, G.A., "Large-scale heat exchange and ice production in the central arctic", *J. Geophys. Res.*, vol.87 (1982), p. 7971.

45/ Svendsen, E.K. *et. al*., "Norwegian remote sensing experiment: Evaluation of the Nimbus-7 scanning multichannel microwave radiometer for sea ice research", *J. Geophys. Res.,* vol. 88 (1983), p. 2781.

46/ Norsex Group, "Norwegian remote sensing experiment in a marginal ice zone", *Science,* vol. 220 (1983), p. 781.

47/ Cavalieri, D.J., P. Gloersen, and W.J. Campbell, "Determination of sea ice parameters with the Numbus-7 SMMR," *J. Geophys. Res.*, vol. 89 (1984), p. 5355.

DATA ACQUISITION AND FLIGHT PLANNING FOR AGRICULTURAL APPLICATIONS*

C.A. Hutton and K.F. Link
INTERA KENTING
Ottawa, Ontario, Canada

ABSTRACT

This paper describes the factors to be considered when planning a data acquisition campaign utilizing a Synthetic Aperture Radar (SAR) system. To minimize the complexity of the analysis, the paper focuses primarily on an agricultural programme.

The ability to monitor agricultural resources is an economic concern for most countries. Monitoring agricultural resources requires an accurate and timely method. The ability to predict yields and monitor areas under production will allow appropriate pricing policies to be developed. Information can be used by planners to set up irrigation policies, anticipate difficulties in soil conditions, organize trade policies, verify inventories, monitor insurance claims and set crop subsidies.

The dynamic nature of crop growth and development requires a timely, accurate and reliable monitoring tool. The spatial requirements for monitoring crops can be fulfilled by utilizing Visible and Infra-red (VIR) satellites. However, these sensors are not adequate for monitoring the dynamics of crop growth. Synthetic Aperture Radar (SAR) sensors, unrestricted by atmospheric conditions that plague the VIR sensors and capable of recording unique ground information that VIR sensors cannot capture, have become a new source of information.

The success of any SAR programme will partially depend on the quality and timeliness of the data acquired. Flight planning or data acquisition requires an a priori knowledge of the needs for which the data will be used, a phenological understanding of the agricultural targets of interest, a well-defined ground truth acquisition plan and an in situ information assessment.

Itemized in this paper are the target and sensor parameters which need to be assessed prior to planning a SAR mission or in addition to a satellite acquisition, the mechanics of flight planning and ground information programmes and the post flight requirements.

---

* This paper, which was presented at the United Nations/Food and Agricultural Organization of the United Nations/European Space Agency Microwave Workshop organized in co-operation with the Government of Brazil, São José dos Campos, Brazil, 19-23 November 1990, does not necessarily reflect the views of the United Nations.

The sensor parameters reviewed are the wavelength, polarization, incidence angle and look direction variations available, which relate to assessing programme needs. The general target parameters reviewed are the roughness, dielectric properties and geometry of the agricultural target.

INTRODUCTION

It is essential when considering a Synthetic Aperture Radar (SAR) acquisition that a series of factors be identified. The level of effort expended prior to SAR data acquisition will have an impact on the usefulness of the subsequent data. A detailed project outline or set of objectives is needed. This outline should address: the information that is necessary to fulfil this need or objective; an assessment of whether SAR is the best tool; a determination of whether a combination of SAR and VIR is best; and the timing of data acquisition, location, etc. An assessment of the expected interaction between the microwave and target of interest should be undertaken through literature searches, previous experience or any other available means.

Once the objectives have been identified, the site and a crop calendar(s) should be identified and designed. A detailed ground information plan is necessary to assist in the analysis of the data after acquisition. Finally, after the flight, an in-situ assessment of the SAR data should be made. It is also useful to assess the products needed and the ability of the user organization to handle the incoming data. Image analysis systems or interpreters will be needed to conduct much of the data assessment. Excessive quantities of data are not necessary to fulfil user needs and often cannot be processed by the user organization.

When planning a data acquisition campaign there are a wide variety of factors which will influence the actual data collection. Many of these factors are influenced by the flexibility of the sensor and many more by the nature of the application. For example, an airborne SAR has a very wide range of incidence angles, illumination directions, and scheduling flexibility when compared to the relatively fixed orbits of the forthcoming satellites. On the other hand, a spaceborne SAR can greatly reduce the cost of data acquisition. When using an airborne sensor the increased flexibility provides numerous other factors to affect the programme design.

The effect of the various characteristics, and hence the design of the programme, is largely dependent on the specific application and the exact nature of the target. For example, when planning a geologic programme the flight direction may be chosen to enhance the structure of the topography, normally a 20-30 degree offset to the primary geologic feature. In addition, the amount of vertical relief will dictate the flight line spacing to minimize or maximize the shadows and to control the quality of a mosaic product. The illumination direction may also be chosen to provide a direction which cannot be obtained from a passive sensor. The illumination direction should complement the data types which rely on the Sun for illumination, typically allowing only allow east or west looks, not north, south or other directions.

The above example illustrates only a few of the factors to be taken into consideration; however, they must be analyzed in detail to plan the programme to gain the maximum information from the data. To further illustrate how to design a data acquisition programme, the remainder of this paper uses agricultural examples to highlight the importance of the planning process.

SYNTHETIC APERTURE RADAR

Before beginning the outline of the data acquisition or flight planning, a bit of background on microwave interaction with vegetation is necessary to provide the basis for sensor choices, flight times, etc.

The dynamic nature of crop growth and development requires a timely, accurate and reliable monitoring tool. The spatial requirements for monitoring crops can be fulfilled by utilizing Visible and Infra-red (VIR) satellites. However, these sensors are not adequate for monitoring the dynamics of crop growth. Due to the fact that SAR sensors, which are unrestricted by atmospheric conditions that plague the VIR sensors and which can record unique ground information that VIR sensors cannot capture, have become a new source of information.

Sensors operating in the microwave portion of the electromagnetic spectrum can penetrate clouds and operate under most atmospheric conditions. Active microwave sensors or radars, which generate and transmit their own energy, respond to and receive different surface information from that derived from VIR sensors. Microwaves are particularly sensitive to moisture content, structure and roughness of the target, the characteristics that allow distinctive information regarding the surface of the Earth.

Of the airborne SAR sensors available, three are operated by Canadians: the INTERA STAR systems (STAR-I and STAR-2), available on a commercial basis, offers X-band SAR, horizontal-horizontal (HH) polarization, and the Canadian Government's C-band and X-band SAR offer data in HH, vertical-vertical (VV), vertical-horizontal (VH) and horizontal-vertical (HV) polarizations. Other experimental systems are currently under development.

SAR satellites which will be the operational platforms of the 1990s will include SAR sensors in a number of frequencies, polarizations, orbits and a variety of incidence angles.

Canada's RADARSAT satellite, scheduled for launch in 1994, [1] will carry a C-band, horizontally polarized SAR. RADARSAT will orbit the Earth at an altitude of 800 km and provide data in near real time on a three day sub-cycle in four operating modes. These operating modes will provide SAR data with a combination of resolutions and swath widths. The European Space Agency (ESA) will launch ERS-1, a C-band, vertically polarized SAR satellite in late 1991 or early 1992. In addition to the SAR, a number of other microwave sensors will be carried.

The United States' Shuttle programme includes a SAR mission with a payload consisting of C-band, X-band and L-band SARs. Although this mission will be short-lived (approximately 10 days) in comparison with the satellites, the opportunity to study the multi-frequency effects on crop monitoring from a spaceborne platform will be valuable.

Sensor Parameters

Radar remote sensing operates in the microwave portion of the electromagnetic spectrum. The microwave region extends from 0.3 GHz to 300 GHz in frequency or 1m to 1mm in wavelengths. The three wavelengths most frequently used are the C-band, X-band and L-band.

Active microwave sensors or radars transmit microwave energy towards a target (i.e., surface). A portion of the energy, depending on the characteristics of the target, is scattered back to the antenna. The measurement of the intensity, time delay and the phase history of these returned signals are the basis for SAR operation.

Maxwell's equation 2/ describes the behaviour of electromagnetic waves, but for our purposes it is sufficient to note the length or frequency of the wave which will vary and alter the interaction with the surface target. Short wavelengths (e.g., X-band) tend to interact with and provide information about the canopy, while the longer wavelengths (e.g., L-band) will penetrate the canopy and provide information about the soil. Polarization describes the electric vector of propagation associated with the electromagnetic field. Horizontal (H) polarization describes the vector when perpendicular to the plane of incidence while Vertical (V) polarization is in the plane of incidence. With present SAR operating systems the capability exists to acquire data with like polarizations (HH or VV) or cross polarizations (HV or VH) describing the orientation of the transmitted and received signals.

The choice of wavelength has a significant influence on the radar return. The choice of X, C or L-band (the most available systems) is the main determinant of the type and strength of the radar directed at the targets and ultimately the return from them. The X-band data with the shorter wavelengths generally respond to the crop canopy directly and the associated backscatter is highly influenced by the biomass or structure of the crop. The C-band, which has slightly longer wavelengths than the X-band, penetrates the canopy further and provides more information about the internal structure of the crop or, in the case of short crops combined information about the crop and soil. The L-band, which is a long wavelength, usually penetrates the crop canopy and provides information about the soil. These are of course only general guidelines to assist in the choice of frequency selection. Target parameters, in particular moisture, will alter the expected response from the crops.

Polarization, as discussed, can be vertically or horizontally transmitted and received in one or both modes, depending on the capabilities of the sensor. Although work is continuing on the influence of polarization on the expected backscatter from crops, there is evidence to suggest that the structure of certain crops (e.g., wheat) will show a greater or lesser backscatter based on polarization. It appears from recent studies conducted in Canada that with respect to C-band HH polarized waves are penetrating further into the canopy while the VV data are providing more information about the soil surface, or combination of crop and soil.

With any SAR data the ability to acquire suitable data may be influenced by the incidence angle of the sensor. The incidence angle is a system design factor and cannot be altered, but flight lines or data acquisition can be set up to put the ground area of interest "under" certain incidence angles. As an example, ERS-1 data will be collected with incidence angles of approximately 23 degrees. This may influence the choice of these data. With the airborne systems, a wider variety of incidence angles are available but the ground area at any one angle is limited. Understanding the influence of incidence angle is important in order to allow a maximization or minimization of a certain response.

In general, steeper incidence angles will provide a greater penetration of the surface vegetation. For soil information, this may be an important consideration. Most of the present work for identifying incidence angle influence is being conducted with scatterometers. There is, however, sufficient information available to assist a user with flight preparation.

Look direction can be important with surface targets due to the frequency of ploughed rows or crop rows which increases the responses from the target if oriented perpendicular to the look direction of the radar. During flight planning, if the region under study includes crops with this type of structure, it is preferable to design the flight lines to minimize this effect.

In general, the three ground factors to which radar responds are geometric, dielectric and conductive. Geometric factors of crop type include structure, height, growth stage and roughness. Dielectric properties include soil or plant moisture. Conductive factors include density, height and condition of the target. These factors, however, are not the only ones controlling the backscatter responses from the targets in the present work, nor do they reflect the exhaustive list of possibilities.

A radar image is composed of a series of grey tones representing the relative backscatter from the targets. The grey tones over a homogeneous area on a radar image are proportional to the average return of power strength.

The radar returns from a target depend upon both the strength of the transmitted energy and the reflecting or scattering capability of the target. Most radar targets scatter with various strengths along different axes. The strength of the return signal is dependent on the amount of scattering, reflecting and attenuation that occurs before reception at the antenna. Each target on an image is characterized by a unique set of measurable properties represented by the backscatter in the radar image.

Data Acquisition

The priority consideration in programme design is the problem of identification and statement of objectives or needs. Once you have identified your needs, a determination of the sensor(s) available, whether preferred or required, is necessary. The capability to undertake in both terms of equipment and personnel needs, and the products necessary, are identified. In addition to collection of the SAR data, a detailed ground information programme is usually necessary. The greater the level of this effort, the greater the impact on the overall programme. Although time, personnel and capital will dictate potentials in this area, an organization's ability to process and store the data should be considered, because reams of data which are unusable indicate a poor allocation of funds. Consequently, a detailed cost analysis should be performed that indicates both the airborne and the ground-based segment for data acquisition plus the data processing and analysis segments.

Optimal Programme

An optimal data collection programme for agricultural applications will usually include some or all of the following; multi-frequency, multi-date and multi-polarized SAR data. It should also include a detailed ground information plan and air photos or satellite VIR imagery. The most feasible combination of these items is suggested.

Ground Truth and Crop Calendars

A crop calendar describes the progression of the crop through detectable and/or agronomically significant events in its life cycle. A crop calendar is usually developed on a regional basis due to climatic and soil variations which will influence cropping practices. A diagram or chart indicating at a glance the radar backscatter phenomena which might be expected with certain dates and associated image is extremely useful. Additional information should include soil maps and climatic information.

Target Parameters

Target parameters can be broken down into two main subdivisions: vegetation and soil. Vegetation target parameters include plant height, the percentage of ground covered by green, brown and no biomass, the health or condition of the plant, the density, leaf area index, moisture content or biomass, row direction, growth stage, crop type or structure, weed infestation, salinization, etc. Information concerning these parameters should be collected at least in a qualitative manner; quantitative measurements, however, are always preferred. More detailed information and alternate methods of data collection are available. The ground information needed concerning the soil itself includes the roughness, type, moisture and the tillage direction.

A number of instruments are now available or are under design for collecting some of the ground information identified. One example of these is the Portable Dielectric Probe, commercially available in the United States, which directly measures the soil's dielectric constant. More information concerning these instruments can be found in many of the international journals. Ground truth collection needs to be acquired as closely as possible to the date of flight (the same day if possible) to ensure that the factors influencing the radar are documented accurately.

Post-Flight Data Collection

Most airborne SAR systems provide the user with the means to supply a quick-look paper image product after the plane has landed. It is extremely useful to use this quick-look product to reassess the expected SAR backscatter from certain crops or targets. This exercise has been coined "anomaly assessment" because most experienced SAR interpreters have an idea of the expected backscatter based on the crop calendar which was designed for use with each study. Using the quick-look, the region under study is revisited to identify any fields or target features which respond differently than expected. This information is then documented for future work. This type of analysis comes in very useful later in the lab when a detailed classification or other assessment technique is conducted. In the lab, an unusual finding may be explainable. Simple changes, such as a field being unexpectedly ploughed by the owner, may save many hours or days of analysis time.

CONCLUSIONS

In order to maximize the utility of SAR data the user must have a good understanding of the interaction expected from his target. This target extraction can be extremely complex in some applications, and the programme designer can utilize the flexibility of the sensor to minimize unexpected results. Selection of the appropriate imaging parameters can greatly increase the value of the data set, allowing the user to emphasize his target of interest and minimize the confusion with similar targets.

Data collection should include surface truth activities and post-flight analysis, corresponding as close as possible to the time of flight. Accurate and complete mission planning is essential to the success of a SAR programme. With poor planning the entire opportunity may be lost, at great expense to the user.

NOTES

1/ Shaw, E. and E.l. Langham, "RADARSAT: Canada's Microwave Satellite," Proceedings of IGARSS'89, Vancouver, B.C. (1989).

2/ Elachi, C., "Introduction to the Physics and Techniques of Remote Sensing," Wiley Series in Remote Sensing (1987), pp. 413.

3/ Ibid.

4/ Cihlar, et al., "Procedures for the Description of Agricultural Crops and Soils in Optical and Microwave Remote Sensing Studies," Int. Remote Sensing, vol. 8, No. 3 (1987), pp. 427-439.